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Feasibility study of tokamak, helical and laser reactors as affordable fusion volumetric neutron sources

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Applicability of tokamak, helical and laser fusion reactors as a volumetric fusion neutron source has been examined using the systems codes that have been used for the conceptual design of DEMO and commercial reactors. This study has clarified the characteristics of reactor-based volumetric neutron sources that can be designed based on the current physics and engineering basis with a reasonable running cost ($\sim$5B JPY/year). Though the achievable neutron flux is 3–4 orders lower than that of accelerator driven neutron sources, tokamak and helical neutron sources can provide a much larger irradiation area for the test of large components. Laser neutron sources have both high operability and tritium breeding capacity. These reactor-based neutron sources also serve an integrated test bed of the entire reactor system.

To realise a fusion power plant, an irradiation test of the reactor materials and components by fusion neutrons are necessary. At present, accelerator driven neutron sources (e.g., A-FNS by Japan) have been planned because of the high cost performance in terms of the maximum available neutron flux. For example, A-FNS can achieve the neutron production rate of 6.8×10^{16} n/s and the neutron flux in the high irradiation region is $> 10^{18}$ n/m^2/s, which corresponds to > 20 dpa/year for reduced-activation ferritic/martensitic steel. A concern is that the high irradiation volume is quite limited ($\sim$0.5 L). In contrast, reactor-based volumetric neutron sources can provide a larger irradiation space with a monoenergetic and a homogenous neutron field. Even if the neutron flux is low, such irradiation environment is useful for the test of large components or multiple samples. These reactor-based neutron sources can also serve as an integration test bed of the entire reactor system. Therefore, reactor-based neutron sources that can be constructed based on the current physics and engineering achievements with a reasonable running cost are attractive. In this study, tokamak, helical and laser reactors are selected because sophisticated design activities and related R&Ds towards a commercial power plant have been conducted. The authors have developed and improved systems codes for tokamak, helical and laser reactors [1-3]. This study has been conducted by making full use of these system codes.

Availability and running cost are important factors to discuss the design feasibility. Considering steady-state operation capability and the electricity expenses (0.5B JPY/MW), the injection power of $\sim$5 MW and the injection energy of $\sim$100 keV are assumed for the NBI heating for tokamak and helical reactors. Adoption of superconducting coils is assumed to achieve steady-state operation and the thickness of shielding blanket (SB) is determined to suppress the nuclear heating on the coils below 0.1 mW/cc. For a laser reactor, 10 kJ/100 Hz laser system is assumed based on the current design of the diode-pumped solid state laser module: 10 J/100 Hz. To reduce the construction cost, the minimum reactor size and the magnetic field strength that ensure sufficient shielding thickness were examined for tokamak and helical reactors. Thus, the net tritium breeding ratio (TBR) over unity and electricity generation are not considered as prerequisites. To reduce the amount of an external supply of tritium, breeding blankets are installed as long as space is available and DD start-up is considered.

In the case of a tokamak reactor, conservative physics parameters are assumed: Greenwald density limit ratio $n/n_{\mathrm{GW}} < 1$, normalized beta $\beta_N < 2$ and confinement improvement factor to the H-mode scaling $H_H < 1$. The CS coil radius is set to enable an inductive operation with the duration of 1 hour. Regarding the availability, a conservative value of 50% is assumed. It was found that the above-mentioned conditions are satisfied with the SB thickness of 30 cm with the major radius $R = 3.5$ m and the magnetic field strength $B = 3.4$ T. Assuming the NBI power of 5 MW, D-T thermal fusion power of ~0.5 MW is expected. In the case of the beam-bulk fusion induced by injecting D beam in T plasma, fusion power of $\sim$ 10 MW is achievable. Consequently, the achievable neutron production rate is 3.6×10^{18} n/s. The neutron flux of 1.8×10^{16} n/m^2/s can be provided in an area of $\sim$200 m^2. The neutron production rate is almost proportional to the NBI power, whereas the reactor size will be 1.1 times larger when the NBI power becomes 2 times larger. Because the construction cost is roughly proportional to the cube of the reactor size and the annual operation cost strongly depends on the construction cost, the cost of neutrons decreases with the increase of the NBI power or the reactor size. Therefore, the optimization of the design should be conducted by considering the allowable construction cost or annual operation cost.

In the case of a helical reactor, the reactor size strongly depends on the space between the plasma and the helical coils. To ensure the minimum SB thickness of 25 cm, $R = 6$ m and $B = 4$ T are required with the helical coil current density achieved in LHD: 35 A/mm^2. Assuming the NBI power of 5 MW, the D-T thermal fusion power of $\sim$0.1 MW is achievable with the physics conditions that have been realized in the LHD experiment. In the case of the beam-bulk fusion by injecting D beam in T plasma, fusion power of $\sim$5 MW can be expected. Consequently, the achievable neutron production rate is 1.8×10^{18} n/s. The neutron flux of 4.5×10^{15} n/m^2/s can be provided in an area of $\sim$400 m^2. Because there is no need for the plasma current drive, the requirement on the NBI system is moderated and a year-long steady-state operation is expected.

In the case of a laser reactor, the neutron yield of $\sim 10^{13}$ has been achieved with the injection laser energy of 10 kJ using a target design called LHART. The minimum chamber size is determined by the heat load limit. In this case, heat load is sufficiently small if the chamber with a practical size (e.g., a diameter of > 0.1 m) is adopted. Assuming the repetition rate of 10 Hz by considering the injection capability of the fuel target, the achievable neutron production rate is 10^{14} n/s. Consequently, achievable neutron flux is 8×10^{14} n/m^2/s with a spherical chamber that has the diameter of 0.1 m. Irradiation area and neutron flux can be flexibly varied by the chamber design. Because there is no limit on the space for blanket modules, the blanket design can be optimised for tritium breeding for net TBR > 1. The operation of multiple (up to 10) chambers is also possible by steering the laser beams. Though the duration of the operation depends on the fuel target injection capability, a year-long operation is assumed here.

The design parameters are summarised in Table 1. The issues for the increase of neutron flux has been clarified, which directly relate to the priority issues for the reactor development.

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[1] T. Goto et al., Plasma Fusion Res. **9** (2014) 3405140.
[2] T. Goto et al., Nuclear Fusion **51** (2011) 083045.
[3] T. Goto et al., Nuclear Fusion **49** (2009) 075006.

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