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Parameter Requirements for D-^{3}He Helical Reactors

MITARAI Osamu, SAGARA Akio[1], IMAGAWA Shinsaku[1], TOMITA Yukihiro[1],
WATANABE Kiyomasa[1] and WATANABE Tsuguhiro[1]

Kyushu Tokai University, Toroku 862-8652, Japan
[1]National Institute for Fusion Science, Toki 509-5292, Japan
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Abstract

Parameter requirements are studied for D-^{3}He helical reactors with three sizes based on the shifted large helical device (LHD) plasma (the major radius R = 3.6 m) with R = 14.5~18.5 m, and for a compact reactor based on a quasi-poloidal stellarator with R = 10.36 m. To achieve ignition in a D-^{3}He helical reactor with the magnetic field strength B_o = 6 T, the confinement should be improved up to >2.4 times larger than the present LHD confinement, and the volume averaged beta $\langle\beta\rangle$ = 14~21 %, the hot ion mode with the peak ion to electron temperature ratio T_i/T_e>1.5 and the heating power of 200~300 MW are necessary. The lower beta would be obtained in a larger machine and the neutron power can be reduced to 60 ~ 90 MW for 3 GW fusion power.

Keywords:

D-^{3}He fusion, Helical reactor, Ignition, Low neutron power, LHD, Quasi-poloidal stellarator

1. Introduction

A D-^{3}He fusion is attractive for achieving a safer and cleaner fusion reactor. Therefore, ARTEMIS studies had been conducted using the field reverse configuration (FRC) for achieving D-^{3}He fusion by Momota *et al.* [1]. Recent demonstration of feasibility of a D-^{3}He spherical tokamak reactor [2] also urges studies of a D-^{3}He helical reactor, which has not been explored yet. To see the future prospect of LHD type experiments and other type of helical machine, it is important to study parameter requirements in a D-^{3}He helical reactor. In contrast to a D-^{3}He tokamak system requiring the large plasma current more than 50 MA, the possible plasma current-free operation in a helical system is advantageous because of no risk of the disruption. In this paper, we examine parameters to be necessary for D-^{3}He helical reactors based on the 0-dimensional analysis and the international stellarator scaling (ISS95 scaling) [3] for three sizes of helical reactors and a quasi-poloidal stellarator (QPS) [4].

2. Formalism and ignition control algorithm

We have used the 0-dimensional particle and power balance equations for D-^{3}He, D-D and D-T fusions. The hot ion mode of T_i/T_e = 1.5 is assumed in the power balance equation. As clear transition from L to H mode in LHD has not been observed, the density limit has been used for control of the heating power [5], which is mainly different from the tokamak reactor analysis. Therefore, the applied external heating power is set to expand the density limit larger than the operating density by 2 %. Fusion power is regulated by a proportional-integration-derivative (PID) controller with the fusion power signal, and fuel ratio of D and ^{3}He is controlled by a proportional-integration (PI) controller with fuel ratio signal. This D and ^{3}He fuel ratio control is important to achieve the low neutron power mode. We employ the confinement factor γ_{LHD} over the present LHD confinement time of 1.6 × τ_{ISS95} in this study with τ_{ISS95} being the confinement time given by ISS95 scaling. This ISS95 scaling created for a helical system is the second different point from the tokamak reactor analysis. The effective minor radius $\bar{a}$ expressing the helical plasma makes a helical system analysis similar to a tokamak reactor analysis. All the effective particle confinement time ratios of the deuterium, helium-3, tritium, 14 MeV proton and 3.7 MeV alpha particle to the energy confinement time are assumed to be 2, and the prompt loss of all the fusion products to be zero. The density and temperature profiles are assumed as parabolic. As the beta value is lower than that in ST, ignition is sensitive to the wall reflectivity (R_{eff}), then R_{eff} = 0.99 has been chosen.

3. Temporal evolution of the plasma parameters to ignition

D-^{3}He ignition is possible for a helical reactor with R = 14.5 m, $\bar{a}$ = 2.6 m, B_o = 6 T, and the high beta of $\langle\beta\rangle$ ~ 18 %. Confinement factor with γ_{LHD} = 2.4 provides ignition with the external heating power of P_{EXT} = 300 MW for the fuel ratio of D:^{3}He = 2:1, leading to high neutron power of P_n = 184 MW.

Corresponding author's e-mail: omitarai@ktmail.ktokai-u.ac.jp

The lower neutron power of P_n = 61 MW is achieved after switching the fuel ratio setting value to the helium rich state of D:^{3}He = 0.45:0.55 at 70 sec as shown in Fig.1. The external heating power is lowered to P_{EXT} = 200 MW in the case of higher confinement factor of γ_{LHD} = 3. The final beta reaches $\langle\beta\rangle$ ~ 21 %, and the peak electron density $n(0)$ is 3.92×10^{20} m^{-3} and the peak ion temperature $T_i(0)$ is 115 keV. The total Bremsstrahlung loss power P_B = 0.9 GW to the first wall and the total plasma conduction loss P_L~1.8 GW to divertor should be converted to the electricity. For the thermal conversion efficiency of 40 %, the electrical power output may be 1.1 GW. Average heat flux to the first wall (Γ_h) is 0.74 MW/m^2 which is manageable in the present technology and the average neutron wall loading (Γ_n) is 0.04 MW/m^2, where the blanket could be used for a reactor life time. The divertor heat flux P_{div} to the assumed wetted area with 1 m width of two legs is ~10 MW/m^2, which is calculated by $P_{div} = P_L/(2\pi R \times 1\text{m} \times 2\ \text{legs})$, providing a challenging task especially for the shorter wetted width [6]. The detailed parameters are listed in Table 1. As the ratio of the bremsstrahlung and conduction loss power, which determines the divertor heat flux, depends on the confinement law itself (the power law of the density and the external heating power in the ISS95 scaling), it is difficult to change this ratio by confinement improvement.

The larger machine such as $R/\bar{a}$ = 16.6 m/2.9 m can also reach ignition with γ_{LHD} = 3.0 and P_{EXT} = 250 MW, and the slightly larger neutron power of P_n = 87 MW is obtained for the fuel ratio of D:^{3}He = 0.52:0.48 at $\langle\beta\rangle$ ~ 16 %. For the

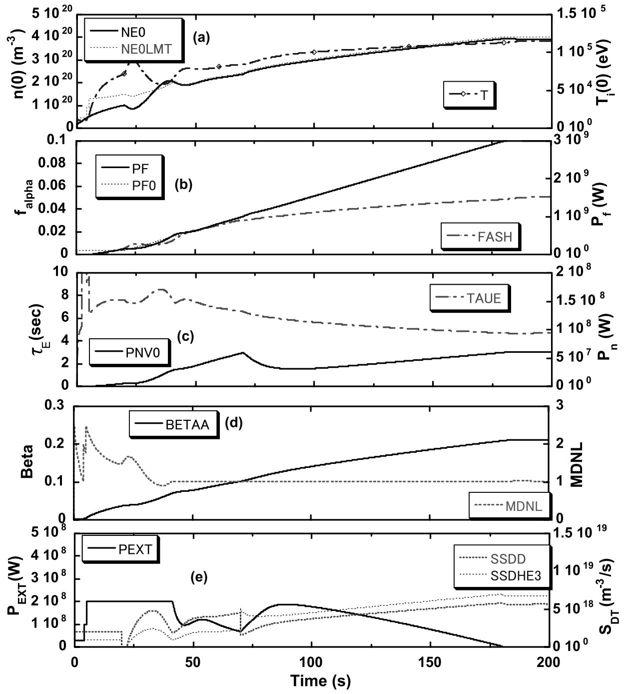

Fig. 1 Temporal evolution of the plasma parameters in the low neutron power mode in the D-^{3}He helical reactor with R = 14.5 m. (a) The peak density $n(0)$, density limit $n(0)_{LMT}$ and peak ion temperature $T_i(0)$, (b) fusion power P_f, fusion power set value P_{f0}, and alpha and proton ash fraction f_{alpha}, (c) the energy confinement time τ_E and the total neutron power P_n, (d) beta value β and density limit factor $n(0)_{LMT}/n(0)$ and (e) the external heating power P_{EXT} and deuterium S_D and helium-3 fueling rate S_{HE3}.

Table 1. Parameters for LHD type D-^{3}He Helical Reactors

Major radius:	R	14.47 m	16.62	18.46
Effective minor radius:	$\bar{a}$	2.585 m	2.908	3.232
Toroidal field:	B_o	6.0 T	6.0	6.0
Plasma volume	V_o	1908 m^3	2774	3806
Average plasma surface area	S_o	1476 m^2	1988	2355
Blanket thickness:	Δ_{BT}	0.933 m	1.115	1.297
Rotational transform:	$\iota_{2/3}$	0.92	0.92	0.92
Heating power:	P_{EXT}	200 MW	250 (300)	250 (300)
Confinement factor:	γ_{LHD}	2.4~3.0	2.5~3.0	2.5~3.0
Confinement time:	τ_E	4.7 s	5.0	6.3
Ash density fraction:	f_{alpha}	5.1 %	4.4	4.9
Effective ion charge:	Z_{eff}	1.73	1.68	1.68
Fuel ratio:	n_D:n_{He3}	0.45:0.55	0.52:0.48	0.52:0.48
Electron density:	$n(0)$	3.92×10^{20}	3.3×10^{20}	2.72×10^{20}
Ion temperature:	$T_i(0)$	115	100	107
Toroidal beta value:	$\langle\beta\rangle$	21.1%	15.9	14.0
Fusion power:	P_f	3 GW	3	3
Neutron power:	P_n	61 MW	87	86
Bremsstrahlung loss:	P_B	906 MW	818	803
Synchrotron radiation loss				
to the wall:	P_{sw}	89.3 MW	94.6	143
for energy conv.:	P_{sH}	99.2 MW	105.1	158
Plasma conduction loss:	P_L	1847 MW	1897	1810
Electric power (η_c = 40 %)	P_e	~1100 MW	~1000	~1000
Average neutron wall loading	Γ_n	0.04 MW/m^2	0.046	0.036
Average heat flux:	Γ_h	0.74 MW/m^2	0.53	0.47
Divertor heat load	Γ_r	~10 MW/m^2	9	7.8

smaller confinement factor of γ_{LHD} = 2.5, the larger heating power of P_{EXT} = 300 MW is required. For somewhat larger machine such as $R/\bar{a}$ = 18.5 m/3.2 m, the beta value can be reduced to $\langle\beta\rangle$ ~ 14 % for similar performances as listed in Table 1. This is because that the longer confinement time in the larger machine leads to the lower density, and hence lower beta.

We note that the same size of D-T reactor (R = 14.5 m, $\bar{a}$ = 2.6 m, B_o = 6 T) does not require any improvement in confinement (γ_{LHD} = 1.0) for D-T ignition in the case of η_α = 1 (no prompt loss of alpha particles) and $\tau_\alpha{}^*/\tau_E$ = 3 (alpha ash confinement time to the energy confinement ratio). The initial heating power is 70 MW, and the final beta is $\langle\beta\rangle$ ~ 2.7 %, which is within the present experimental value. On the other hand, a D-^{3}He helical reactor is demanding in beta, confinement factor and divertor heat flux when LHD type machine is assumed. Therefore, we have further searched for the other type of helical machines suitable for a D-^{3}He fusion such as quasi-poloidal stellarator proposed by Oak Ridge National Laboratory group [4]. In this machine, the high beta of $\langle\beta\rangle$ = 15~23 % and long confinement time of τ_E ~ 6 × τ_{ISS95} = 3.75 ×(1.6×τ_{ISS95}) are expected for the aspect ratio of A = 3.7. The large confinement factor compensates the relatively low rotational transform of ι = 0.4 at the center. We have calculated the temporal evolution of the plasma parameters in the compact QPS D-^{3}He reactor with R = 10.36 m, $\bar{a}$ = 2.8 m, and B_o = 6 T as shown in Fig. 2. For γ_{LHD} = 3.7, the confinement fraction of the 14 MeV proton and 3.7 MeV alpha particle η_p = η_α = 97 % and D:^{3}He = 0.49:0.52, we have obtained the following parameters such as P_n = 72 MW, Γ_n = 0.06 MW/m^2, Γ_h = 0.84 MW/m^2, the alpha and proton ash fraction f_{alpha} = 5.0 %, P_L = 1.9 GW, P_B = 0.88 GW, the total synchrotron radiation loss power P_S = 0.15 GW, τ_E~4.1 s, $n(0)$~4.29×10^{20} m^{-3}, $T_i(0)$~111 keV and $\langle\beta\rangle$ = 22.7 % in the steady state phase.

4. Summary and issue

To achieve ignition in a D-^{3}He helical reactor with R = 14.5 m to 18.5 m and B_o = 6 T, the confinement should be improved up to >2.4 times larger than the present LHD confinement, and $\langle\beta\rangle$ = 14~21 %, the hot ion mode of T_i/T_e>1.5 and the heating power of 200~300 MW are necessary. Neutron power is 60~90 MW. However, divertor heat load is challenging. Larger machine has a lower beta due to the lower density and larger confinement time. While these parameter improvements are challenging for LHD type machine, QPS is quite interesting for D-^{3}He fusion.

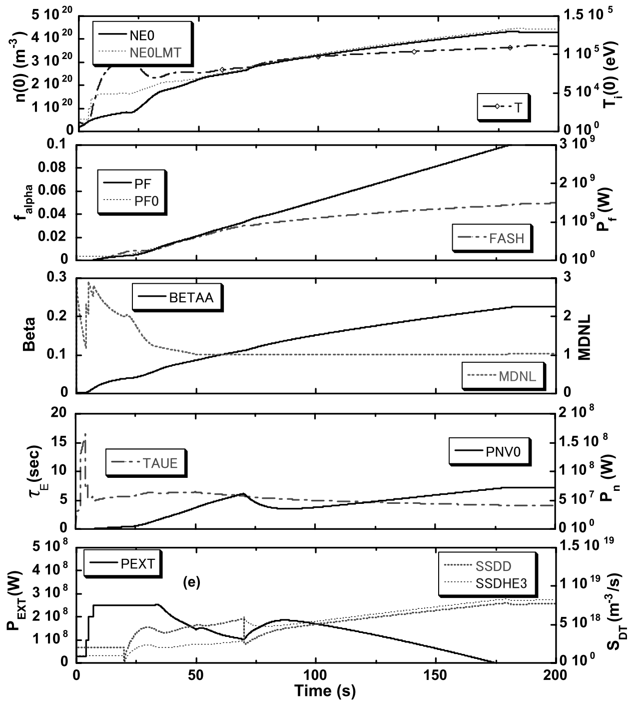

Fig. 2 Temporal evolution of the plasma parameters in the compact QPS D-^{3}He helical reactor with R = 10.36 m.

Acknowledgments

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