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Aspect ratio dependencies of D–^{3}He fueled tokamak reactors

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Abstract

Ignition capability is studied and compared for two types of D–^{3}He spherical tokamak (ST) and medium aspect ratio tokamak (MT) reactors. The required power fraction to ions for maintaining the hot ion mode, which is indispensable for D–^{3}He fusion, is smaller in a ST reactor than that in a MT reactor due to the lower synchrotron radiation loss. It is found that the nuclear elastic scattering capable of supplying 40% of the fusion energy to ions is enough to maintain the hot ion mode in the D–^{3}He ST reactor with the high wall reflectivity. For achieving the D–^{3}He MT reactor, the power fraction to ions should be additionally increased.

Keywords: D–^{3}He fusion; Spherical tokamak; Medium aspect ratio tokamak; Hot ion mode

1. Introduction

A D–^{3}He advanced fuel fusion is attractive for realizing a safer and cleaner fusion reactor [1]. Recent successful experiments of the plasma current ramp-up by the vertical field and heating power [2,3] encourage parameter studies of D–^{3}He spherical tokamak (ST) and medium aspect ratio tokamak (MT) reactors because the large plasma current is necessary for D–^{3}He fusion. Additionally, the hot ion mode ($T_i > T_e$) is indispensable to achieve D–^{3}He fusion to cope with the synchrotron radiation loss. In order to achieve the hot ion mode, the most of the fusion produced energy should go to ions in the high density regime where the coupling between ions and electron energy is strong. In this paper, the required power fraction to ions is estimated to achieve D–^{3}He ignition, and machine and plasma parameters are compared for D–^{3}He ST and MT reactors with: (1) $R = 5.8$ m, $a = 3.4$ m, $A = 1.7$, $B_o = 4.4$ T, $\kappa = 3.0$, and $I_p = 90$ MA, and (2) $R = 7.5$ m, $a = 3.2$ m, $A = 2.33$, $B_o = 7.0$ T, $\kappa = 2.2$, and $I_p = 50$ MA, respectively.

2. Formalism for calculation

We have used the zero-dimensional particle and power balance equations for D–^{3}He, D–D, and D–T fusions, and the separate ion and electron energy balance equations to study the hot ion mode correctly. The

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global confinement enhancement factor γ_{HH} of 1.8–2.5 over the IPB98(y,2) scaling is used, and the ion to electron energy confinement time ratio of $\gamma_c = \tau_{Ei}/\tau_{Ee} = 2$ and 4 is assumed in this study. The sum of the electron and ion conduction loss is equal to the total conduction loss given by the global confinement scaling. The effective particle confinement time of D, ^{3}He, T, p, and ^{4}He particles to the energy confinement time is assumed to be $\tau_p^*/\tau_E = 2$, and the prompt loss of the fusion products to be zero. Major and minor radii are selected to have an average heat flux of around 1.0 MW/m^2, and the electricity would be converted from the radiation heat to a first wall and energy to a divertor with thermal conversion efficiency of 40%. Fuel ratio of D and ^{3}He is 2:1 in the initial heating phase to increase the reactivity, and then fueling of D and ^{3}He is controlled by proportional–integral-derivative (PID) based on the fuel ratio and total fusion power. The external heating power is feedback-controlled to maintain the H-mode as basically discussed in earlier papers [5]. The power fraction to ion is assumed to be 50% during the initial external heating phase [6] and the required power fraction to ions from the fusion product heating is estimated in the range between 30 and 80%.

The plasma current is calculated using the plasma circuit equation with the poloidal coil currents, the non-inductive driven current, and the bootstrap current with $I_{BS}/I_p = C_{BS}\sqrt{\varepsilon}\beta_p$ (C_{BS} is the given coef-

Table 1
Parameters of D–^{3}He MT and ST reactors

	(1)	(2)	(3)	(4)
Major radius, R (m)	7.5	7.5	5.6	5.6
Minor radius, a (m)	3.2	3.2	3.4	3.4
Aspect ratio, A	2.33	2.33	1.7	1.7
Toroidal field, B_0 (T)	5–7.0	5–6.5	4.4	4.4
Maximum field, B_{max} (T)	16.0	14.8	20.5	20.5
Plasma current, I_p (MA)	50	50	90	90
Heating power, P_{EXT} (MW)	180 → 0		250 → 0	
Confinement factor over IPB(y,2) scaling, γ_{HH}	2.0	2.0	2.5 → 2.0	2.5 → 2
Global confinement time, τ_E (s)	12	11	16.5	16.7
Proton and Helium ash density fraction, f_{ash} (%)	9.5	8.9	10.4	11.0
Ion to electron energy confinement time ratio, τ_{Ei}/τ_{Ee}	2	2	2	2
Wall reflectivity, R_{eff}	0.95	0.95	0.9	0.7
Density profile, α_n	1.0	1.0	0.5	0.5
Temperature profile, α_T	1.0	1.0	1.0	1.0
Electron density, $n(0)$ (m^{-3})	3.1×10^{20}	3.0×10^{20}	2.5×10^{20}	245×10^{20}
Greenwald factor, $n(0)/n(0)_{GW}$	1.33	1.3	0.77	0.75
Power fraction to ion, F_{ion}	0.7	0.6	0.4	0.62
Ion temperature, $T_i(0)$ (keV)	110	110	135	145
Electron temperature, $T_e(0)$ (keV)	75	79	110	104
Temperature ratio, $T_i(0)/T_e(0)$	1.47	1.4	1.22	1.39
Toroidal beta value, β (%)	12.2	14.3	40.0	39.0
Poloidal beta value, β_p	1.78	1.8	1.3	1.3
Normalized beta value, β_N	5.4	5.9	6.5	6.4
Allowable normalized beta, β_{Nlimit}	6.0	6.0	7.8	7.8
Fusion power, P_f (MW)	3000	3000	3000	3000
Neutron power, P_n (MW)	100	100	62	61
Bremsstrahlung loss, P_b (MW)	952	960	1450	1301
Synchrotron radiation loss, P_s (MW)	973	862	416	581
Plasma conduction loss, P_L (MW)	968	1074	1074	1057
Electric power ($h_c = 40\%$), P_e (MW)	1028	1044	1132	1137
Average neutron wall loading, Γ_n (MW/m^2)	0.061	0.06	0.035	0.034
Average heat flux, Γ_h (MW/m^2)	1.1	1.05	1.05	1.06
Double null divertor heat flux, Γ_{div} (MW/m^2)	10.3	11.4	15.2	15.3