AC Operation of a D-^3He Tokamak Fusion Reactor

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AC OPERATION OF A D-^{3}He TOKAMAK FUSION REACTOR

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Abstract

We propose an inductive alternating current (AC) D-^{3}He tokamak reactor (R= 9.5 m, a = 2.8 m, B_t= 10 T and I_p= 53.6 MA), operated in the first stability regime, with a small current-drive power ~ 500 kW in the plasma side, and ~2 MW in the transformer side. The high electron temperature $T_e(0)$ ~ 62.5 keV together with the high bootstrap current fraction > 70 % decreases the plasma resistance (to less than 1 nΩ) and the loop voltage (~10 mV range), and then prolongs the pulse length to more than 15 hours. The ignition characteristics of a D-^{3}He tokamak reactor are analyzed by the operation path method on the $P_{ht}\tau_E^2$-T plane and POPCON for different confinement scalings.

1. Introduction

The steady-state operation is the best operation scenario in the tokamak reactor. However, the non-inductive current drive schemes, such as neutral beam and radio-frequency current drive studied so far, are not proven yet to be effective in an ignited regime due to the penetration problem of the neutral beam in a high density regime, the damping effects of the RF wave by fusion particles, and the low efficiency for driving the current (large recirculation power). These problems can be removed by inductive current drive using an Ohmic transformer and the quasi-continuous alternating current (AC) operation mode with a thermal and electric energy storage unit to provide a continuous electric power output. Inductive current drive has been so far the most reliable, simple and efficient method, and complicated physics is not expected in the ignited regime. Fish scales on the first wall for the synchrotron current drive, which plays a special role in the D-^{3}He tokamak, are not needed, facilitating a simple structure of the first wall.

The disadvantage of the thermal fatigue of the first wall may be addressed by employment of coolant flow control where, during the rampdown and up phase, the coolant flow in the first wall is reduced, so that the temperature in the first wall may be kept constant. Mechanical fatigue problems of toroidal coils by an oscillating out-of plane load can also be alleviated by long pulse operation for many hours. Thus an AC scheme can become a basic operation scenario in a D-^{3}He tokamak fusion reactor, and a non-inductive current drive scheme can be a back up or auxiliary system for controlling the plasma current profile if it is needed.

The first experiment on AC operation has been achieved in the small STOR-1M tokamak [1] and AC experiments in a large machine have been recently demonstrated in JET [2]. An AC tokamak reactor (ACTR) has been proposed for D-T fuels based on these experimental results [3].

In this paper, we propose an AC operated D-^{3}He tokamak reactor with a small current drive power and a simple first wall structure, and consider what condition and machine size are necessary to have AC operation.

2. Flux Condition for AC Tokamak Operation

An AC tokamak must satisfy "the flux condition for AC operation" [3], to achieve AC operation with a one cycle pulse length ($2T_{AC}$) longer than that of single swing operation (T_1). The total transformer flux (Φ_t) available in the tokamak must be larger than the inductive flux (Φ_L) by a factor of three, $\Phi_t/3 > \Phi_L$. More precise flux condition for AC operation is given by

$$\Phi_t/3 > (\Phi_L - \Phi_R/3), \qquad (1)$$

where Φ_R is the resistive flux during the current ramp-up and ramp-down phase given by $\Phi_R \sim 0.4\,\mu_o R\, I_p$. This condition favors a high aspect ratio with a large major radius, because a larger transformer flux can be employed.

It is difficult to satisfy this condition in the D-^{3}He tokamak reactor because the plasma current and the inductive flux are larger than that in the D-T tokamak reactor. Therefore, the machine size optimization has to be done carefully to achieve AC operation in the D-^{3}He tokamak reactor. The Ohmic transformer radius is calculated by

$$R_{OH} = R - a - \Delta_{sl} - \Delta_{sh} - \Delta_{tr} - \Delta_{bc} - \Delta_{oh} \qquad (2)$$

where Δ_{sl} is the scrape-off layer thickness, Δ_{sh} is the thickness of the shield, Δ_{tr} is the width of the toroidal coil, Δ_{bc} is the width of the backing cylinder for the toroidal coil radial movement protection, and Δ_{oh} is the half thickness of the Ohmic transformer coil. The total transformer flux is then given by

$$\Phi_t = 2\pi R_{OH}^2 B_{OH} + \Phi_{VE}, \qquad (3)$$

where B_{OH} is the maximum magnetic field in the transformer solenoid coil, Φ_{VE} is the flux contribution from the outer vertical equilibrium-coils, which is about 300 Vsec for I_p ~ 50 MA. In this calculation, we assume Δ_{sl} = 0.1 m, Δ_{sh} = 0.7 m, Δ_{tr} = 1 m, Δ_{bc} = 0.5 m, and Δ_{oh} = 0.5 m. The inductive flux is calculated by $\Phi_L = L_p I_p = \mu_o R I_p[\log(8R/(a l_k)) - \ell_i/2 - 2]$ with $l_k^2 = [1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)]/2$, δ the plasma triangularity, and κ the plasma elongation.

From the flux relationship shown in Fig. 1 for the case of B_t = 10 T, a= 2.8 m, κ = 2, δ = 0.7, q_a = 2.8, and ℓ_i = 1, we see that the critical major radius for AC operation is almost R = 9.5 m corresponding to I_p = 53.6 MA, where $\Phi_t/3 > (\Phi_L - \Phi_R/3)$ is marginally satisfied for B_{OH} = 18 T. Here we have R_{OH} = 3.9 m, Φ_t = 2020 Vsec, Φ_L = 739 Vsec, and Φ_R = 256 Vsec. In the following we use

these machine parameters for a D-^{3}He AC tokamak reactor.

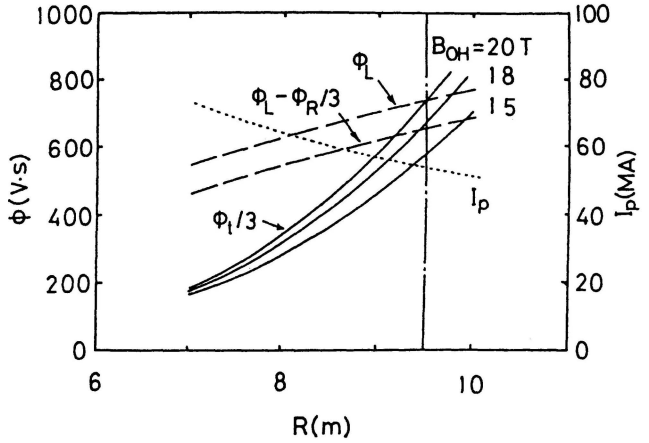

Fig.1 Flux relationship vz the major radius for a = 2.8 m, δ = 0.7, κ=2, q_a = 2.8, B_t = 10 T, and ℓ_i =1 .

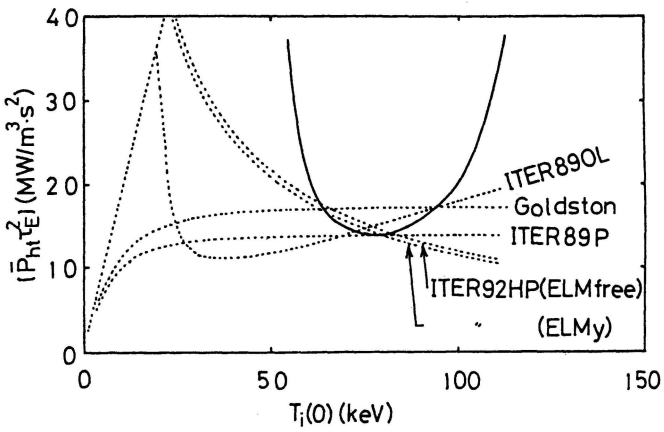

Fig.2 The operation paths of the D-^{3}He tokamak reactor and the ignition boundary on the $P_{ht}\tau_E^2$-T plane. The parameters are $\alpha_n = \alpha_T$ =1, n(0) = 4.3x10^{20} m^{-3}, $T_i(0)/T_e(0)$ =1.2, η_{p14} = 0.9, Z = 7, Z_{eff} = 1.7, f_z = 0.5 %, $f_\alpha = f_p$ = 0.02, f_D = 0.452, f_{3He} = 0.226, f_H =0.1 and R_{eff} =0.965.

3. Ignition Characteristics in the D-^{3}He Tokamak Reactor

3.1. Operation Path and Ignition Boundary.

The operation paths [4] for ITER89P, off-set linear (OL), and Goldston L-mode scalings with the confinement enhancement factor of γ_H = 4, and ITER92-H-P ELM free (γ_H = 1.15) and ELMy (γ_H = 2) H-mode scalings and the ignition boundary are shown in Fig. 2 for $\bar{n}_e$ ~ 2.9x10^{20} m^{-3}. Here, ITER92-H-P ELM free and ELMy H-mode scalings [5] are given, respectively, by

$$\tau_{E,th} = \gamma_H\ 0.032\ I_p^{0.95} B_t^{0.2} A_i^{0.45} R^{1.95} \kappa^{0.65} (a/R)^{0.05} \times n_e^{0.3} (\times 10^{19} m^{-3})/P_H^{0.65} \quad (4)$$

$$\tau_{E,th} = \gamma_H\ 0.034\ I_p^{0.9} B_t^{0.05} A_i^{0.4} R^{2.1} \kappa^{08} (a/R)^{0.2} \times n_e^{0.3} (\times 10^{19} m^{-3})/P_H^{0.65} \quad (5)$$

The total net heating power P_H was replaced by $P_{ht}2\pi^2 R a^2 \kappa$ for the analyses. The ignition regime exists for all scalings assumed here with the plasma parameters: the parabolic density and temperature profile $\alpha_n = \alpha_T = 1$, peak electron density $n_e(0)$ = 4.3 x10^{20} m^{-3}, the ion to electron temperature ratio $T_i(0)/T_e(0)$ = 1.2, the 14 MeV proton confinement efficiency η_{p14} = 0.9, average impurity charge Z = 7, the effective ion charge Z_{eff} = 1.7, impurity fraction to the electron density f_z = 0.5 %, alpha and proton particle ash fraction to the electron density $f_\alpha = f_p$ = 0.02, fuel density ratio of deuterium and ^{3}He n_D/n_{3HE} = 2, the hole fraction f_H = 0.1 and wall reflectivity R_{eff} = 0.965 for the synchrotron radiation loss [6]. The high confinement factor of ~ 4 over ITER89P L-mode scaling may be a reasonable extrapolation from the V-H mode in DIII-D experiments [7]. H-mode scaling has to be further improved by up to a factor two to reach D-^{3}He ignition as shown here. The mass factor is taken to be A_i = 2 because ^{3}He fuels do not show any confinement improvement in JET [8].

3.2. Operating Point and Auxiliary Heating Power in POPCON

To have a fusion power ~ 3 GW and a large bootstrap current, the operating point A as shown in Fig. 3 has been selected at $n_e(0)$ = 4.3x10^{20} m^{-3} and $T_i(0)$ ~ 75 keV on the ignition boundary in POPCON for ITER89P scaling with γ_H = 4, where β_p~ 1.62 and $T_e(0)$ ~ 62.5 keV. The toroidal beta value $<\beta_t>_{op}$ ~ 6.5 % at the operating point is smaller than the Troyon beta limit $<\beta_t>_{TROY}$ = 3.5 I_p/aB_t ~ 6.7 %.

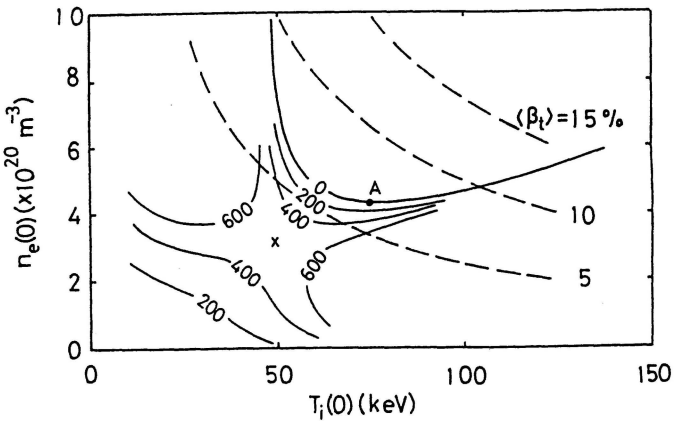

Fig.3 Operating point (A) in POPCON for ITER89P scaling with γ_H = 4 in the D-^{3}He tokamak reactor.

The actual fusion power is P_f ~ 3.7 GW, where the bremsstrahlung loss is P_b ~ 1.4 GW, the synchrotron radiation loss is P_s ~ 1.5 GW, and the plasma conduction loss is P_L ~ 0.8 GW. The electric power output from thermal conversion due to the bremsstrahlung and synchrotron radiation losses may be $P_{e,b}$~ 880 MW for the conversion

efficiency of 40 %, and the one by the rectenna conversion of the synchrotron radiation is $P_{e,s}$ ~ 360 MW for the waveguide loss of 20 % and conversion efficiency of 80 %. The thermal wall loading is $(P_b+P_s)/S_{wall}$ ~ 1.4 MW/m^2, and the divertor heat load is P_L/S_{div} ~ 27 MW/m^2 with a 0.5 m wide divertor target plate.

The auxiliary heating power P_H is rather large, ~ 475 MW for $T_i(0)/T_e(0)$ = 1.2. To reduce the heating power, we examine the effect of spin polarization of D and ^{3}He ions on the 50 % fusion reactivity enhancement (γ_{spin} = 1.5), and hot ion mode operation as shown in Fig. 4.

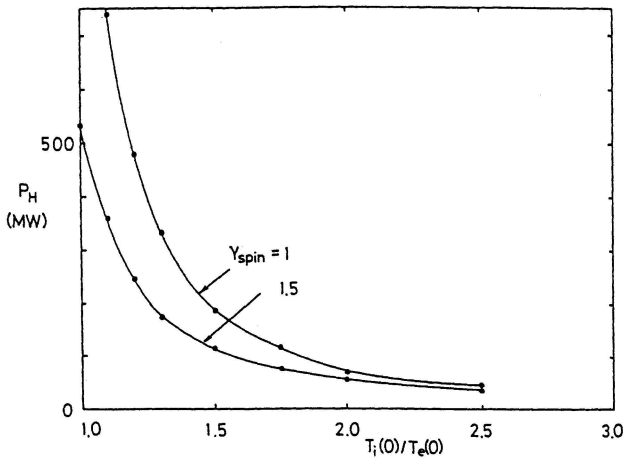

Fig.4 Dependence of minimum auxiliary heating power on the hot ion mode operation, and spin polarization effect for ITER89P scaling with γ_H = 4. (q_a=2.8).

It is found that the heating power to reach ignition is sensitive to the ion to electron temperature ratio $T_i(0)/T_e(0)$; for example P_H ~ 70 MW for the hot ion mode of $T_i(0)/T_e(0)$ = 2 and unpolarization (γ_{spin} = 1.0). Spin polarization is especially effective in reducing the heating power in the regime with a low ion to electron temperature ratio; for example, spin polarization (γ_{spin} = 1.5) yields P_H~ 245 MW for $T_i(0)/T_e(0)$ = 1.2.

Low toroidal field operation decreases the synchrotron radiation, and therefore it can reduce the heating power. The minimum heating power is 340 MW at B_t = 7 to 7.5 T for $T_i(0)/T_e(0)$ = 1.2 and γ_{spin} =1.0 as shown in Fig.5, where the plasma current is proporional to the toroidal field for the same safety factor and plasma shape parameters. Combination with spin polarzation further reduces the heating power to 120 MW. In the current startup phase this operation scenario may be employed, and the toroidal field can be increased after passing the saddle point in POPCON, and then ignition can be reached in the first stability regime with enhanced synchrotron radiation losses.

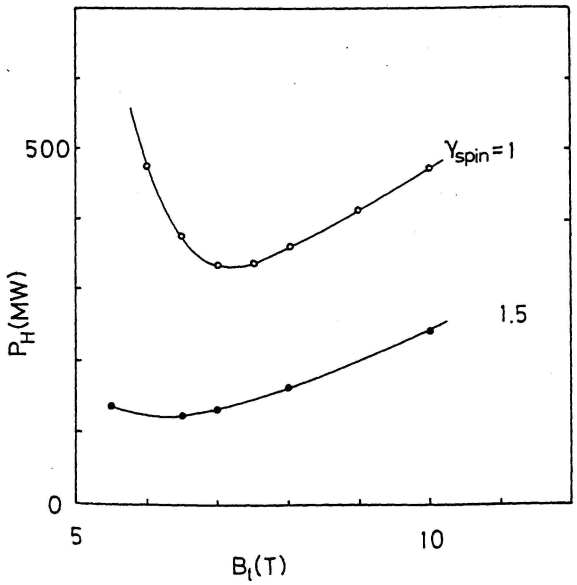

Fig.5 Dependence of minimum auxiliary heating power on the toroidal field and spin polarization effect for ITER89P scaling with γ_H = 4. (q_a=2.8)

4. AC Operation with Large Bootstrap Current Fraction

At the operating point (A) on Fig. 3, the neoclassical plasma resistance is R_{NC} = 0.77 nΩ for $T_e(0)$ = 62.5 keV, therefore the loop voltage is $V_{loop} = R_{NC}(1 - I_{BS}/I_p)I_p$ = 9.8 mV for I_{BS}/I_p = 76 % at β_p =1.62. Here, the bootstrap current fraction is given by [9]

$$I_{BS}/I_p = \sqrt{\frac{a}{R}\kappa}\,\beta_p\, Q_\alpha\, 0.0673 \left\{ \frac{1}{\alpha_n + \alpha_T - 0.421} - \left(1 - \frac{q(0)}{q_a}\right) \frac{1}{\alpha_n + \alpha_T + \gamma - 0.421} \right\}, \qquad (6)$$

where γ = 0.3 and $Q_a = (\alpha_n + \alpha_T + 1)(9.64\alpha_n + 0.642\alpha_T)$, which provides a smaller bootstrap current fraction than ITER scaling [10]. The current drive power in the plasma side is therefore quite small, $P_{CD} = V_{loop}I_p$ ~ 0.53 MW. The power for driving the transformer action ($P_{CD,T}$) can be estimated by the time derivative of the stored energy in the transformer (W_{OH})to be as small as $P_{CD,T} = d(W_{OH})/dt$ ~ 1.9 MW. Compared to this value, the **non-inductive current drive method needs a prohibitively large current drive power.** For example, for a non-inductive current drive efficiency $\eta_{CD} = R\bar{n}_e I_p(1 - I_{BS}/I_p)/P_{CD}$ ~ 1x10^{20} A/Wm^2, which is assumed to be almost the double of the presently obtained maximum value, the current drive power is P_{CD} ~ **350 MW** in the plasma side for driving the same plasma current of I_p = 53.6 MA with a high density plasma of $\bar{n}_e$ = 2.9x 10^{20} m^{-3} and the high bootstrap current fraction of I_{BS}/I_p = 76 %. Therefore, the operational power of the non-inductive current drive system is about **700 MW** for a conversion ef

ficiency of 50 %, resulting in a very small net electric power output from the fusion plant.

The first positive pulse length is $T_1 = (\Phi_t - \Phi_L - \Phi_R)/V_{loop}$ ~ 29 hours, and the subsequent AC pulse lengths are $T_{AC} = (\Phi_t - 2\Phi_L)/V_{loop}$ ~ 15 hours. In Fig.6, we show the numerically calculated AC current waveform in the D-^{3}He tokamak. It is seen that the first pulse is almost twice of the subsequent AC pulse.

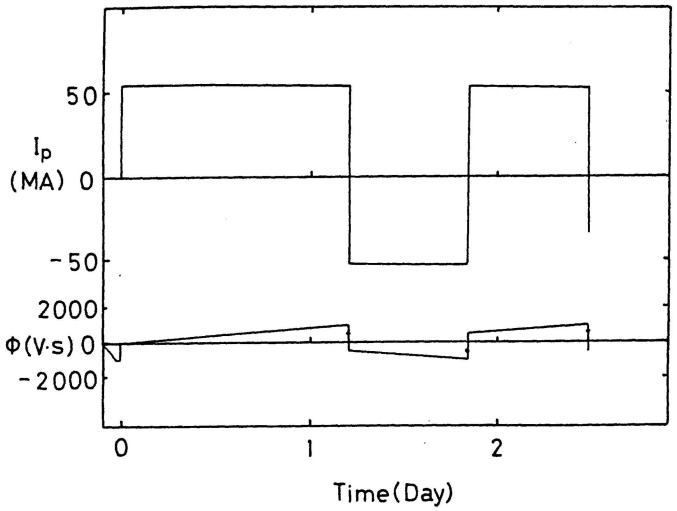

Fig.6 AC current waveform and flux variation of the transformer in the proposed D-^{3}He AC tokamak reactor.

We have surveyed more parameters of the D-^{3}He AC tokamak reactors as listed in Table 1.

5. Summary

We have presented the AC operated D-^{3}He tokamak reactor with the parameter of R= 9.5 m, a= 2.8 m, B_t= 10 T, δ= 0.7, κ= 2, q_a= 2.8, I_p= 53.6 MA and more than 15 hours AC pulse length. The inductive current drive power is only 500 kW in the plasma side and 1.9 MW in the transformer side, which is more than three hundred times smaller than the non-inductive drive method. The auxiliary heating power to reach ignition is rather large ~ 475 MW for $T_i(0)/T_e(0)$= 1.2. Spin polarization, hot ion mode operation and low toroidal field operation in the current startup phase may reduce the heating power further.

Thus an "advanced inductive operation" such as an AC operation mode with the high bootstrap current fraction may be the only one solution for driving the large plasma current with high density in a D-^{3}He tokamak fusion reactor, and a non-inductive current drive scheme can serve an auxiliary system for controlling the plasma current profile.

Table 1. Machine parameters for the proposed D-^{3}He AC tokamak reactor with $T_i(0)/T_e(0)$=1.2. B_{OH}= 18 T and Φ_{VE} = 300 Vsec are used. The height of the operation path $[P_{h,net}\tau_E^2]_{op}$ is calculated using ITER89P scaling with γ_H = 4.

Reactor		DHETR-9.5		
R	(m)	9.5		
a	(m)	2.8		
q_a		2.8	2.8	2.6
δ		0.5	0.7	0.7
I_p	(MA)	47.1	53.6	57.7
γ_H		4.5	4.0	4.0
$n_e(0)$	($\times 10^{20} m^{-3}$)	4.32	4.30	4.20
$T_i(0)$	(keV)	75	75	75
P_f	(GW)	3.75	3.7	3.6
$[P_{h,net}\tau_E^2]_{op}$	(MW/m^3s^2)	15.1	14.9	16.9
AC Capability		AC	AC	AC
R_{OH}	(m)	3.9		
Φ_t	(Vsec)	2020		
Φ_L	(Vsec)	686	739	796
R_{NC}	(nΩ)	0.77	0.77	0.77
β_p		1.85	1.62	1.45
I_{BS}/I_p		0.87	0.76	0.68
V_{loop}	(mV)	4.7	9.8	14
T_1	(h)	65	29	18
T_{AC}	(h)	38	15	8.5
$<\beta_t>_{op}$	(%)	6.5	6.5	6.4
$<\beta_t>_{TROY}$	(%)	5.8	6.7	7.2

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