18PB-037

Strategy for the Development of Tokamak DEMO Reactor with Hybrid Scenario

ハイブリドシナリオを用いたトカマク原型炉開発戦略

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A tokamak DEMO concept using the hybrid scenario (HbS) is proposed. The HbS is quite convenient for the DEMO development with high reliability and high flexibility. A high aspect-ratio line would be desirable for the safety and HbS. An example of HbS DEMO with major radius R_0 ~9 m and Q = 20~30 is shown, where the long pulse length of 4~10 hours is achievable for the moderate bootstrap current fraction f_{BS} = 0.5~0.6, current drive efficiency γ_{CD} = 0.3~0.4 and ohmic current fraction f_{OH} = 0.1~0.3.

1. Introduction

After the Fukushima nuclear disaster March 2011, the R&D policy for nuclear fusion DEMO reactors has been reconsidered in Japan [1]. In order to reduce the neutron load and heat load for the plant safety, the net electric power P_{net} could be lowered to several hundred MWe routinely from the previous value of P_{net} ~ 1 GWe (; fusion output power P_F ~ 3 GW).

A steady-state tokamak reactor (SSTR) with the efficient utilization of the boot-strap current was proposed [2]. To generate P_F = 2.5 GW, the major radius of SSTR was designed as R_0 = 9 m. Afterwards to pursue the economy of construction cost, a compact tokamak reactor concept with sliming the central solenoid coil (SlimCS) was set forth, where R_0 was decreased to 5.5 m maintaining P_F = 3 GW [3]. On the other hand, the pulse tokamak reactor concept has survived. An inductive-drive long-pulse tokamak (IDLT) with P_{net} = 1 GWe had R_0 = 10 m [4]. The neutron wall load in these reactors was Γ_n ~ 3 MW/m^2, and could bring about the wall melt due to the uncontrollable decay heat under the severe accident. Recently a renewal DEMO conceptual design was proposed, where $P_{net} \approx$ 800 MWe and $\Gamma_n \approx$ 1 MW/m^2 with $R_0 \approx$ 8 m [5]. The equipped CS coil is able to supply the magnetic flux required for the current ramp-up. On the other hand in EU for a long time, there have been a strategy of the pulsed operation to accelerate a DEMO program [6].

The present report proposed a tokamak DEMO concept using the hybrid scenario (HbS), which is planned for ITER to test the various engineering components towards DEMO with high reliability, high neutron fluence and long pulse length [6,7]. The fraction of the non-inductive current, f_{NI}, including the bootstrap current is expected to be 40~60% in the ITER HbS, and to be larger than 70% in the DEMO HbS. The CS coil supplies the magnetic flux for the ohmic current over several hours. The HbS will enhance the operational flexibility of the DEMO reactor to realize finally the nuclear fusion commercial reactor, whichever steady-state reactor or long-pulse reactor.

2. Requirement of Confinement Performance and Current Drive Power

The tokamak reactor should have a certain plasma current I_p for high Q (fusion gain) operation to generate the net electric power output. The minimum condition $H_H I_p A$ > 50 MA was given in Ref. [6], where H_H is the confinement improvement factor from H98 scaling and $A = R_0/a$ is the aspect ratio. Taking account of the fuel dilution ($C_f = 2n_{DT}/n_e$), the core radiation cooling ($C_r = 1 - P_{rad}^{core}/P_{abs}$), the operation density ($N_{GW} = \pi a^2\langle n_e\rangle/I_p$: m^2, 10^{20}/m^3, MA) and the operation-temperature effect, the condition is approximately expressed as

$$H_H I_p A > 12\langle T\rangle^{0.56}\Big/\left(C_f^2 C_r\right)^{1/3}\left(1+5/Q\right)^{1/3} F(N_{GW})\ \text{MA} \quad (1)$$

assuming the averaged temperature 10 keV < $\langle T\rangle$ < 20 keV, and the degradation factor $F(N_{GW})$ < 1 at the high density N_{GW} ~ 1. When the fuel dilution and the core radiation are small, $C_f = C_r = 0.85$, the condition is $H_H I_p A$ > 50 MA for $\langle T\rangle$ = 10 keV and $H_H I_p A$ > 75 MA for $\langle T\rangle$ = 20 keV. Design parameters in Ref. [5], $I_p \approx$ 14 MA, $A \approx 3.4$ (R_0 = 8.2 m, a = 2.4 m, κ = 1.85), $\langle T\rangle \approx$ 20 keV, $Q \approx 20$, $H_H \approx 1.5$ and N_{GW} = 0.82, satisfy this condition.

The fusion output power is estimated as

$$P_F \approx 0.07\left(\kappa/R_0\right)\left(C_f N_{GW}/H_H\right)^2\left(H_H I_p A\right)^2\langle T\rangle^{1.5}\ \text{MW} \quad (2)$$

The design value of P_F = 1400 MW in Ref. [5] agrees with this estimation. Under the condition (1), both P_F and Γ_n are decreased with the increase of A by fixing a, N_{GW} and $\langle T\rangle$; $P_F \sim 1/A$ and $\Gamma_n \sim 1/A^2$. If we increase $H_H I_p A \sim A^k$ and $\langle T \rangle \sim A^{1.8k}$ by fixing a and N_{GW}, we can choose $P_F \sim A^0$ and $\Gamma_n \sim 1/A$ with k = 1/4.7 or $P_F \sim A$ and $\Gamma_n \sim A^0$ with k = 2/4.7. From the viewpoint of safety (low Γ_n), a high aspect-ratio line would be desirable.

The boot-strap current fraction $f_{BS} \sim \beta_p/A^{1/2}$ is approximately given by

$$f_{BS} \approx 0.5\left(A/3.4\right)^{1/2}\left(H_H N_{GW}\langle T\rangle/15\right)\left(50/H_H I_p A\right) \qquad (3)$$

where we refer to an ITER steady-state operation parameter; $f_{BS} = 0.5$ at $A = 3.4$, $H_H = 1.6$, $N_{GW} = 0.8$, $\langle T \rangle = 12$ keV and $I_p = 9$ MA. When $H_H I_p A$ = 50~75 MA and $\langle T \rangle$ = 10~20 keV, the f_{BS} value is (0.33~0.44) $\times H_H N_{GW}$. It is difficult to achieve $f_{BS} > 0.6$ within a realistic HH factor < 1.3.

The current drive power for the HbS operation is

$$\begin{aligned} P_{CD} &= \left(1/\gamma_{CD}\right) n_{20} R_0 I_p \left(1 - f_{BS} - f_{OH}\right) \\ &= \left(1/\pi\gamma_{CD} R_0\right)\left(N_{GW}/H_H^2\right)\left(H_H I_p A\right)^2\left(1 - f_{BS} - f_{OH}\right)\ \mathrm{MW} \end{aligned} \qquad (4)$$

where the current drive efficiency γ_{CD} is expected to be improved up to γ_{CD} = 0.3~0.4 even for the electron cyclotron current drive [9,10]. The Q value defined by $Q = P_F/P_{CD}$ is expressed as

$$Q \approx 0.2\,\gamma_{CD}\left(\kappa C_f^2 N_{GW}\right)\langle T\rangle^{1.5}/\left(1 - f_{BS} - f_{OH}\right) \qquad (5)$$

The Q value is able to exceed 25 in a DEMO reactor with $f_{BS} + f_{OH} = 0.8$ at a set of practical parameters; $\gamma_{CD} = 0.3$, $\kappa = 1.8$, $C_f = 0.8$, $N_{GW} = 0.85$ and $\langle T \rangle = 20$ keV. When $f_{OH} = 0$ and $f_{BS} \approx 0.5$ ($H_H \approx 1.3$), the Q value will decrease to ~10 and it will become difficult to generate the net electric output power. To obtain $Q > 25$ without ohmic current contribution, a considerably high performance is required; $f_{BS} > 0.65$ ($H_H > 1.5$), $\gamma_{CD} > 0.4$, $\kappa = 1.8$, $C_f = 0.8$, $N_{GW} = 1$ and $\langle T \rangle = 20$ keV.

In the early phase of DEMO development (conceptual design, engineering design, construction, test operation, initial operation), it is impossible to accurately know the values of C_f, C_r, H_H, $\langle T \rangle$, γ_{CD}, and f_{BS}. These values will be found through the whole DEMO operations. Further improvement of $\gamma_{CD} > 0.4$ will be expected during the DEMO construction phase and operation phase. Therefore the HbS is quite convenient for the tokamak DEMO development with high reliability and high flexibility.

3. Example of HbS DEMO

The radius of the CS coil is larger than 3.5 m to supply the magnetic flux $\Phi_{CS} > 650$ V·s. During the current ramp-up, the external-inductance part $\Phi_{ext} \sim \mu_0 R_0 I_p \sim 150$ V·s spends Φ_{CS}, but internal-inductance and resistive parts should not consume it. The rest of $\Phi_{HbS} \sim 500$ V·s is used for the HbS ohmic current. The plasma resistivity for $\langle T \rangle \approx 20$ keV is lower than $\mathcal{R}_e < 0.002\,A$ V/MA for $(\kappa a/Z_{eff}) > 2.5$ m. The possible flat-top duration is $t_{flattopt} > \Phi_{HbS}/\mathcal{R}_e f_{OH} I_p = 4000/f_{OH}$ sec for $H_H I_p A$ = 75 MA. Long pulse time 4~10 hours will be achievable in a HbS DEMO with f_{OH} = 0.1~0.3. If the TF-coil width is 1~1.5 m, the TF-coil plasma distance is 1.5~2 m and the plasma minor radius a = 2~2.5 m, then the major radius becomes $R_0 \sim 9$ m. This HbS DEMO is not small, but its reliability and flexibility is high enough to realize finally the fusion commercial reactor.

4. Summary

A tokamak DEMO concept using the hybrid scenario (HbS) is proposed. In the early phase of DEMO development, it is impossible to know the accurate performance. They will be found through the whole DEMO operations. The HbS is quite convenient for the DEMO development with high reliability and high flexibility. A high aspect-ratio line would be desirable for the safety and HbS. An example of HbS DEMO is shown; $H_H I_p A \approx 75$ MA, $\langle T \rangle \approx 20$ keV, $H_H < 1.3$, $N_{GW} \approx 0.85$, f_{BS} = 0.5~0.6, γ_{CD} = 0.3~0.4 and f_{OH} = 0.1~0.3 with $R_0 \sim 9$ m, Q = 20~30 and $t_{flattop}$ = 4~10 hours.

Acknowledgments

This work was supported by the Grant-in-Aid for Scientific Research (B) 24360382 from Japan Society for the Promotion of Science. The author thanks Dr. M. Kikuchi, Dr, M. Nakamura and Prof. Y. Ogawa for useful discussions on the DEMO design.

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