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Ignition Condition of Deuterium-Boron Fusion Reactor using LHD-type Magnetic Configuration
LHD磁場を用いる重水素・硼素核融合炉の燃焼維持条件

Tsuguhiro WATANABE, [1]Hideaki Matsuura and [2]Osamu Mitarai
渡辺二太, [1] 松浦秀明, [2] 御手洗修
National Institute for Fusion Science, Toki 509-5292, Japan
[1] *Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, 744 Motooka, Fukuoka 819-0395*
[2] *Liberal Arts Education Center, Kumamoto Campus, Tokai University, 9-1-1 Toroku, Kumamoto 862-8652, Japan*
核融合科学研究所 〒 *509-5292* 土岐市下石町 *322-6*
[1] 九大院工エネルギー量子工学部門 〒 *819-0395* 福岡市西区元岡 *744 W2-833*
[2] 東海大学総合理工学研究科 〒 *862-8652* 熊本市渡鹿 *9-1-1*

We studied the burn control of deuterium-boron fusion reactor, in which the deuterium is primary fuel and the boron is additional fuel. Though the fusion energy which boron generates through the proton boron reaction is only (2 ∼ 5)% of the whole, repetitive injection of solid boron pellets realizes stable burning of a low-temperature and high-density plasma. By adjusting the deuterium and boron supply amounts, a deuterium-boron reactor can be adjusted in a wide range up to a high power output mode with reduced divertor heat flux, from a low power output mode with a minimized divertor heat flux.

1 Introduction

At a deuterium-tritium reactor (DT reactor), power generation unit and fuel production unit are built in as a closely coupled system. Therefore, hurdle to realize the high reliability and the high availability of a DT reactor would be extremely high. On the other hand, the reliability and availability of a deuterium-boron reactor (DB reactor) will be enhanced dramatically, because power generation unit and fuel production unit can be separated completely. Furthermore, since it is not necessary to generate tritium at a DB reactor, the vacuum vessel wall can be constructed with only moderators and reflectors for neutrons. Structure of a DB reactor is greatly simplified.

Reduction of divertor heat flux of a DT reactor, in which only 20% of the fusion energy is released as a charged particle energy, is still desired strongly. Burn control methods for stable operation of the high-density and low-temperature plasma have been proposed [1, 2].

In a DB reactor, since (43 ∼ 63)% of the fusion energy (depending on the nuclear burning conditions) is released as charged particles energy (= P_c), stable control of high-density and low-temperature plasma with enhanced bremsstrahlung radiation loss (= P_{brm}) from the core plasma is essential, to reduce the divertor heat flux (= P_{cnd}) . Since the boron which is the additional fuel of a DB reactor has large charge number ($Z_B = 5$), it increases electron density and P_{brm}. Then, solid boron pellets injection in DB reactor have the similar effects as the impurities (tungsten pellets) injection considered at DT reactors[1]. Furthermore, since the boron injected to a DB reactor are burned off by proton boron reaction, there is no concern that boron accumulates in the reactor core. Then boron injection can be used in a steady state fusion reactor.

In a DB reactor, good confinement for high energy particles (proton and ^{3}He), which are produced by DD and D^{3}He reactions, are necessary. Furthermore, stable confinement performance is necessary at sudden change of Z_{eff} (average Z number of the plasma) and T_e (plasma temperature) accompanied with the boron injection. To this end, the LHD type magnetic configuration which is produced by continuous helical coils is suitable[3]. In this paper, we use the magnetic configuration of $R_0 = 15\,\mathrm{m}$, $B_{ax} = 10\,\mathrm{T}$, $V_{lcfs} = 2000\,\mathrm{m}^3$, and $\gamma = 1.2$, where R_0, B_{ax}, V_{lcfs} and γ are the major radius of the helical coils, field intensity on the magnetic axis, the volume enclosed by the last closed flux surface (LCFS) and the helical coil pitch parameter.

In Sec. 2, we describe the zero dimensional model of a DB rector. In Sec. 3, we describe the numerical results for the burn control of DB reactor by boron pellet injection. We discuss the results in Sec. 4.

2 Zero dimensional model of DB reactor

Nuclear reactions of DB reactor fueled by deuterium and boron are as follows.

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{p}\,(3.03\,\mathrm{MeV}) + \mathrm{T}\,(1.01\,\mathrm{MeV}) \quad (1)$$

$$\mathrm{D} + \mathrm{D} \rightarrow n\,(2.45\,\mathrm{MeV}) + {}^3\mathrm{He}\,(0.82\,\mathrm{MeV}) \quad (2)$$

$$\mathrm{D} + \mathrm{T} \rightarrow n\,(14.06\,\mathrm{MeV}) + {}^4\mathrm{He}\,(3.52\,\mathrm{MeV}) \quad (3)$$

$$\mathrm{D} + {}^3\mathrm{He} \rightarrow \mathrm{p}\,(14.67\,\mathrm{MeV}) + {}^4\mathrm{He}\,(3.67\,\mathrm{MeV}) \quad (4)$$

$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\,{}^4\mathrm{He}\,(8.70\,\mathrm{MeV}) \quad (5)$$

Then the zero dimensional model of a DB reactor is reduced to followings with external heating source (= $P_{\rm aux}$).

$$
\begin{aligned}
\frac{{\rm d}Wp}{{\rm d}t} &= P_{\rm c} - \frac{W_{\rm p}}{\tau_{\rm iss95}} - P_{\rm brm} + P_{\rm aux} && (6)\\
\frac{{\rm d}N_{\rm D}}{{\rm d}t} &= S_{\rm D} - N_{\rm D}\Big[<\sigma v>_{\rm DT} N_{\rm T} \\
&+ \left\{ <\sigma v>_{\rm DDpT} + <\sigma v>_{\rm DDn^3He} \right\} N_{\rm D} \\
&+ <\sigma v>_{\rm D^3He} N_{\rm ^3He} \Big] && (7)\\
\frac{{\rm d}N_{\rm T}}{{\rm d}t} &= <\sigma v>_{\rm DDpT} \frac{N_{\rm D}^2}{2} - <\sigma v>_{\rm DT} N_{\rm D}N_{\rm T} && (8)\\
\frac{{\rm d}N_{\rm ^3He}}{{\rm d}t} &= <\sigma v>_{\rm DDn^3He} \frac{N_{\rm D}^2}{2} - <\sigma v>_{\rm D^3He} N_{\rm D}N_{\rm ^3He} \\
&- \frac{N_{\rm ^3He}}{\tau_{\rm ^3He}} && (9)\\
\frac{{\rm d}N_{\rm p}}{{\rm d}t} &= <\sigma v>_{\rm D^3He} N_{\rm D}N_{\rm ^3He} + <\sigma v>_{\rm DDpT} \frac{N_{\rm D}^2}{2} \\
&- <\sigma v>_{\rm pB} N_{\rm p}N_{\rm B} - \frac{N_{\rm p}}{\tau_{\rm p}} && (10)\\
\frac{{\rm d}N_{\alpha}}{{\rm d}t} &= <\sigma v>_{\rm DT} N_{\rm D}N_{\rm T} + <\sigma v>_{\rm D^3He} N_{\rm D}N_{\rm ^3He} \\
&+ 3 <\sigma v>_{\rm pB} N_{\rm p}N_{\rm B} - \frac{N_{\alpha}}{\tau_{\alpha}} && (11)\\
\frac{{\rm d}N_{\rm B}}{{\rm d}t} &= S_{\rm B} - <\sigma v>_{\rm pB} N_{\rm p}N_{\rm B} - \frac{N_{\rm B}}{\tau_{\rm B}} && (12)
\end{aligned}
$$

Where $W_{\rm p}$ is the plasma thermal energy density,

$$
\begin{aligned}
W_{\rm p} &= \frac{3}{2}\Big[2N_{\rm T} + 2N_{\rm D} + 3N_{\rm ^3He} + \left(\frac{T_{\rm p}}{T_{\rm e}} + 1 \right) N_{\rm p} \\
&+ 3N_{\alpha} + 6N_{\rm B} \Big] T_{\rm e} \times 1.602176462 \times 10^{-19} && (13)
\end{aligned}
$$

and other notations are the usual ones. Since proton are produced by the reactions eqs.(1, 4), it has high energy tail component, which is approximated by high temperature $T_{\rm p}$. Energy confinement time is approximated by $\tau_{\rm iss95}$ with a improving factor $h_{\rm fct}$.

$$
\begin{aligned}
\tau_{\rm iss95} &= \frac{0.2071513306 \times 10^{-8} N_{\rm e}^{0.51} B_{\rm ax}^{0.83} V_{\rm lcfs}^{1.105}}{(P_c + P_{\rm aux} - P_{\rm brm})^{0.59} R_{\rm ax}^{0.455}} \\
&\times \left(\frac{\iota_{2/3}}{2\pi} \right)^{0.4} \times h_{\rm fct} && (14)
\end{aligned}
$$

3 Burn control of DB reactor by constant interval injection of solid boron

Plasma operation contours (POPCON) plot are obtained by a contour plot of $P_{\rm aux}$ with given fuel sources ($S_{\rm D}, S_{\rm B}$) and given fuel densities $N_{\rm B}/N_{\rm D}$ in ($T_{\rm e}$, Ne) plain, at steady state of eqs(6-12). In addition, the POPCON plot shows the stability of burning, fusion output ($P_{\rm c}$ and $P_{\rm n}$), and divertor heat flux $P_{\rm cnd}(= W_{\rm p}/\tau_{\rm iss95})$. If the operation point is on the unstable point, slightly larger size pellets specified by the POPCON plot are injected only for the case of $T_{\rm e} > T_{\rm cntl}$.

A POPCON plot for a low power fusion output mode with a minimized divertor heat flux is shown in Fig.1.

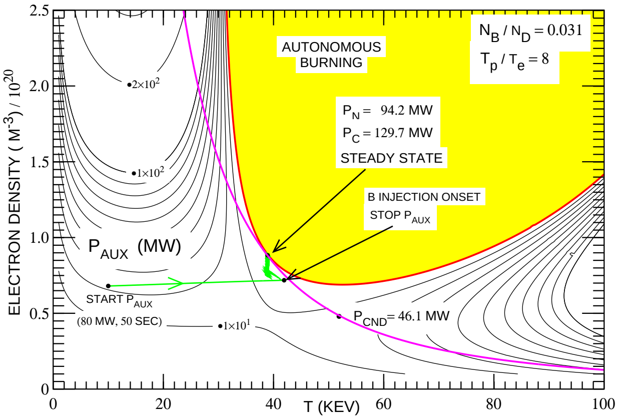

Fig. 1 POPCON plot for minimized divertor heat flux: $T_{\rm cntl}$ = 39keV, $(S_{\rm D}, S_{\rm B}) = (0.9, 3.2) \times 10^{17} \times V_{\rm lcfs}(1/{\rm sec})$. Time trace starting from $T_{\rm e}$ = 10keV is also shown.

An example of a high power output mode with reduced divertor heat flux is shown in Fig.2,

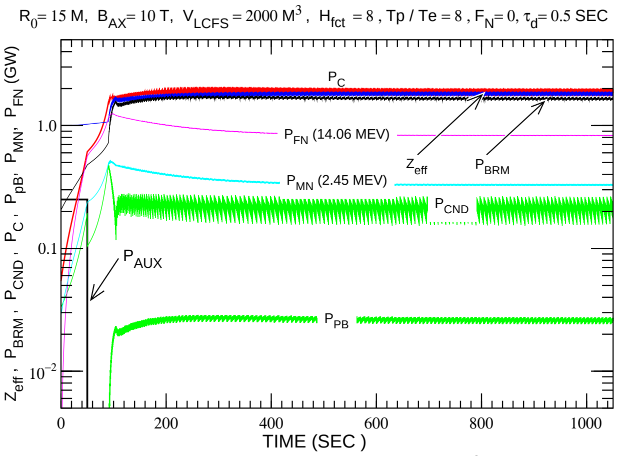

Fig. 2 $T_{\rm cntl}$ = 36keV, $(S_{\rm D}, S_{\rm B}) = (1.15, 1.8) \times 10^{18} \times V_{\rm lcfs}$ (1/sec). Time averages at steady state are $P_{\rm c}$ = 1.86GW, $P_{\rm n}$ = 1.16GW, $P_{\rm cnd}$ = 0.222GW.

4 Discussions

In the present paper, role of high energy tail component of protons are approximated by high temperature $T_{\rm p}$. The calculation of reaction rate using the distribution function of proton and ^{3}He obtained by a Fokker-Planck Boltzmann equation is a future subject. Effect of spatial distribution of temperature and density for burning condition is also interesting. This work was performed with the support and under the auspices of the NIFS Collaborative Research Programs NIFS13KNST062.

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