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LHD Type Proton-Boron Reactor and the Control of Its Peripheral Potential Structure

MATSUMOTO Yutaka*, NAGAURA Tatsuhiko, ITOH Yasuyoshi, OIKAWA Shun-ichi and WATANABE Tsuguhiro[1)]

Hokkaido University, Kita 13, Nish 8 Kita-ku, Sapporo 060-8628, Japan

[1)]National Institute for Fusion Science, Oroshi-cho 322-6, Toki 509-5292, Japan

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Abstract

An advanced Large Helical Device (LHD) type proton(p)-boron(^{11}B) reactor, in which the minority protons are heated by ICRF, is proposed. The ratio of the fusion power to the RF input power is evaluated. Numerical computation of particle orbits shows that the ICRF of LHD can accelerate protons in the p-^{11}B fusion relevant energy. Numerical results also show that the LHD magnetic configuration can confine the high energy ^{4}He well. An active peripheral potential control method and an active ^{4}He ash exhaust scheme are discussed.

Keywords:

LHD, p-^{11}B reactor, ICRF, potential control, ^{4}He ash exhaust

1. Introduction

The drastically improved performance for the plasma heating by the ion cyclotron range of frequency (ICRF) is shown in the third campaign of the Large Helical Device (LHD) experiments in 1999 [1,2]. It is observed that the high energy ion-tail extends to 300 keV and that the electron temperature is raised with the electron-drag relaxation process of the directly heated protons [1,2]. It is also found that protons are heated to the order of 1 MeV and that they are well confined, through the numerical computations of particle orbits under the ICRF heating of LHD. Stimulated by above results, we propose an advanced LHD type fusion reactor which has the same magnetic configuration to LHD and is sustained by ICRF.

Stix has studied the radio frequency (RF) heated tokamak plasma and the D-T reactor based on the analysis of RF heated two-component plasma [3]. It has been found that the ratio of the fusion power to the RF power input can significantly exceed unity. Only D-T fusion reaction, however, has been discussed. In the present paper, we analyze the LHD type proton-boron reactor (p-^{11}B reactor) that is sustained by ICRF. The p-^{11}B reaction,

$$p + {}^{11}B \rightarrow 3\,{}^4He + Q_F,\ (Q_F \simeq 8.7\ \text{Mev}), \quad (1)$$

has the advantages as follows [4,5]:

- Only few neutrons are produced by side reactions at low energy level ($\leq$ 1 MeV). So it is not necessary to consider the neutron wall loading, the severe radiation damage and the radioactivity in structural materials. The blanket is not also needed.
- A large amount of hydrogen and boron is ubiquitous on the earth.

The possibility of the p-^{11}B fusion reactor has been investigated [4-6]. It is pointed out that the economical p-^{11}B reactor would be unlikely since the bremsstrahlung power loss exceeds the fusion output

Corresponding author's e-mail: shopon@fusion.qe.eng.hokudai.ac.jp

power. In such investigations, protons are injected as the neutral beam into the reactor in which the boron plasma is sustained in a steady state. We will argue, however, that the p-^{11}B reactor sustained by ICRF may be possible.

In sec. 2, the possibility of the ICRF sustained p-^{11}B reactor is discussed based on the simplest energy flow model. The particle orbits of the protons under the ICRF heating and the high energy ^{4}He are described in sec. 3. The peripheral potential control and the ^{4}He ash removal method by ECH and ICRF heating in the chaotic field line region are presented in sec. 4. Section 5 is devoted summary and discussion.

2. Possibility of the LHD Type p-^{11}B Reactor

We consider a p-^{11}B reactor consists of the thermal electrons, the thermal borons and the minority protons that are heated by ICRF. We show in Fig. 1 the simplest model of the energy flow in the ICRF sustained p-^{11}B fusion reactor plant. The ICRF power (= P_{RF}) is primarily absorbed into the minority protons and heat them until a fusion reaction occurs. The output power from the fusion plasma (= $P_{RF} + P_F$, where P_F denotes the fusion power) is converted into the electric power with an efficiency η_{PP}. Since a part of the electric power (= P_{RF}/η_{RF}) is needed for the RF oscillator, we can get the net output power (= P_{NET}) reduced to

$$P_{NET} = \eta_{PP}(P_{RF} + P_F) - \frac{P_{RF}}{\eta_{RF}} > 0. \qquad (2)$$

From this relation, it is found that the ICRF sustained p-^{11}B reactor needs

$$Q\ (\equiv P_F/P_{RF}) > \frac{1-\eta_{PP}\,\eta_{RF}}{\eta_{PP}\,\eta_{RF}}. \qquad (3)$$

When we substitute reasonable values for η_{PP} ($\simeq 0.5$) and η_{RF} ($\simeq 0.9$), the above relation reduces to $Q > 1.22\cdots$.

We use the simplest one proton model to evaluate Q of the ICRF sustained p-^{11}B reactor. Protons are heated by ICRF under the electron-drag with the electron density (= n_e) and temperature (= T_e) as:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{P_{RF}}{n_p} - \frac{E - 3T_e/2}{\tau_E}, \qquad (4)$$

reduced to

$$E = E_0 + \left(\frac{\tau_E P_{RF}}{n_p} + \frac{3}{2}T_e - E_0\right)(1 - e^{-t/\tau_E}), \qquad (5)$$

where E and n_p are the energy and density of the proton, and τ_E is the electron-drag time. E_0 denotes the initial energy of proton and is assumed to be 0 hereafter. The value Q becomes

$$Q = \frac{n_p n_B Q_F}{P_{RF}\min(\tau_b, \tau_f)} \int_0^{\min(\tau_b,\tau_f)} \sigma_{pB}(E)\sqrt{\frac{2E}{M_p}}\,\mathrm{d}t, \qquad (6)$$

where τ_b denotes the time when the bremsstrahlung power loss exceeds the fusion power, τ_f represents the time when $n_B \int_0^{\tau_f} \sigma_{pB}\sqrt{\frac{2E}{M_p}}\,\mathrm{d}t = 1$, and M_p is the mass of a proton. σ_{pB} denotes the p-^{11}B fusion cross-section [7]. Equations 5 and 6 are numerically calculated, with using

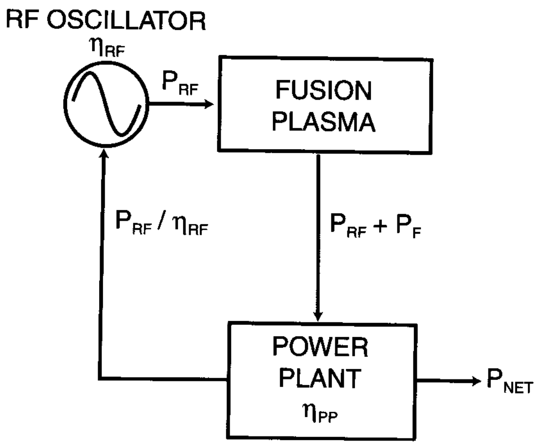

Fig. 1 Simplest model of energy flow in the ICRF sustained p-^{11}B fusion reactor plant.

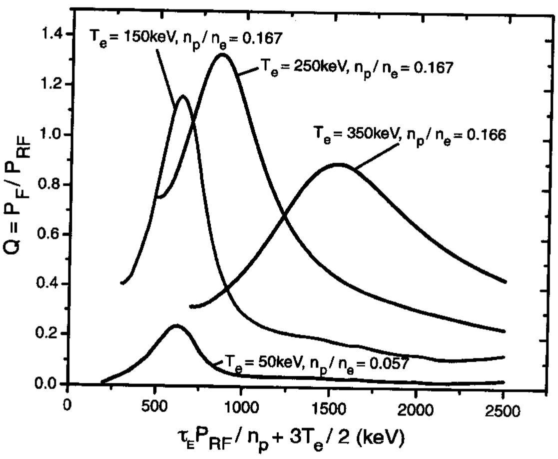

Fig. 2 Relationship between Q, P_{RF}, τ_E, and T_e. n_p/n_e is set to the optimal value for the maximum Q.

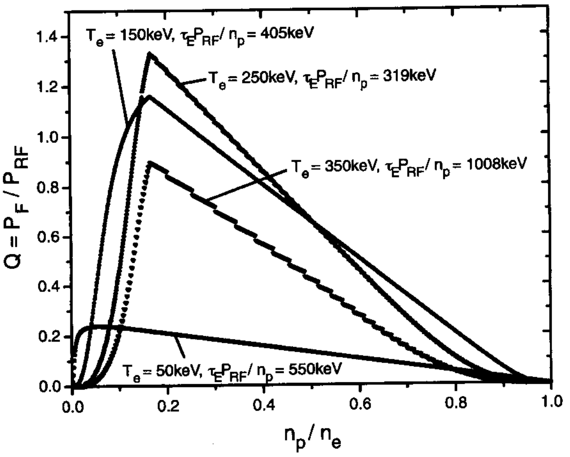

Fig. 3 Relationship between Q, n_p/n_e, and T_e for the case of optimal $\tau_E P_{RF}/n_p$ values.

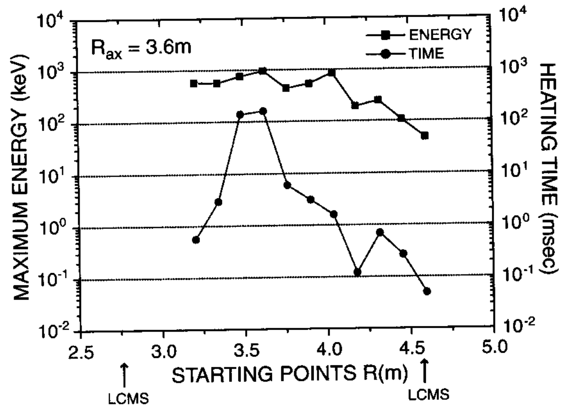

Fig. 4 Maximum energy of ICRF heated proton in LHD with conditions E_0 = 20 kV/m, m = 0, k_R = 0, and B_{ax} = 2.52 T. The starting points are set on Z = 0 plane. The initial energies of protons are set to 1 keV. Heating times to arrive at the maximum energy are also shown.

the trapezoidal rule.

Figure 2 shows the relationship between Q, P_{RF}, τ_E, and T_e. We also show the relationship between Q, n_p/n_e, and T_e for each optimal P_{RF} values, in Fig. 3, which implies the existence of the optimal n_p/n_e. Figures 2 and 3 indicate the existence of the optimal T_e value, also. The combination of these optimal values will bring out the advanced p-^{11}B reactor sustained by ICRF.

3. High Energy Particle Orbit in LHD

There is the transition region in phase space of particles in helical systems. The particle orbits become chaotic in this region. It is essential whether passing particles can transit to the reflected particles without being lost under the ICRF heating process. Then, we trace the orbits of the protons under the ICRF heating in LHD with calculating the equation of motion. In the cylindrical coordinates (R, φ, Z), the ICRF electric field is given as

$$E(R,\varphi,Z,t) = \begin{pmatrix} 0 \\ 0 \\ E_0 \end{pmatrix} \sin(m\varphi + k_R R - \omega t), \quad (7)$$

where m is the toroidal mode number, k_R denotes the radial direction wave number, and ω represents the angular frequency.

The orbits of a proton are calculated until a proton is lost to the vacuum vessel wall,with being changed the starting point and the initial energy of a proton. We also change the magnetic field intensity on the magnetic axis B_{ax}, the wave number k_R and the electric field intensity E_0 of ICRF. The magnetic axis is fixed at R_{ax} = 3.6 m.

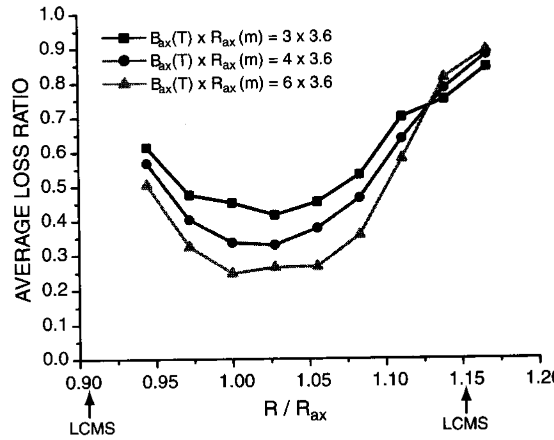

Fig. 5 Loss ratio of ^{4}He in the LHD magnetic configuration. Horizontal axis shows the starting points of tracing ^{4}He in vertically elongated poloidal cross-section. R_{ax} denotes the major radius of the magnetic axis. B_{ax} represents the magnetic field intensity on the magnetic axis. The loss ratio is averaged in the initial pitch angle and in the vertical position which are distributed equal between bottom and top of the LCMS.

Protons are started as passing particles.

As shown in Fig. 4, it is found that the average maximum energy of protons becomes order of 1 MeV except of the peripheral region of the last closed magnetic surface (LCMS). These computation shows that the ICRF of LHD can accelerate protons in the p-^{11}B fusion relevant energy range.

In order to realize the economical p-^{11}B reactor,

^{4}He produced by p-^{11}B reaction is needed to be confined for a long time to heat the plasma. We also trace the guiding-center of 2.9 MeV ^{4}He in LHD during 1000 toroidal turns ($\simeq$ 2.1 ms) and analyze the confinement capability of LHD. Numerical results show that the LHD magnetic configuration can confine the high energy ^{4}He well (Fig. 5).

4. Peripheral Potential Control and ^{4}He Ash Removal in LHD Configuration

In order to realize the p-^{11}B reactor, the good plasma confinement in the core region and the high efficiency exhaust of the ^{4}He ash are important. Therefore, we propose a peripheral potential control method by ECH and ICRF heating in the chaotic field line region just outside the LCMS.

The guiding-center equations show that the deeply trapped particles move along the cross-lines of B = const. plane and $\boldsymbol{B}\cdot\nabla B = 0$ plane. By the numerical analysis of the magnetic structure of LHD, we find the existence of the cross-lines connecting the chaotic field line region and the vacuum vessel wall, as shown in Fig. 6. We call these cross-lines the loss canals. If the resonance position of ECH is placed at loss canals, the peripheral potential will increase due to the rapid loss of the deeply trapped electrons. If the resonance position of ICRF is placed at loss canals, the peripheral potential will decrease due to the rapid loss of the deeply trapped ions. These active potential control methods may be expected as the active control scheme of the core plasma confinement.

The peripheral potential control should be useful for the ^{4}He ash removal. Furthermore, if the ICRF frequency is set equal to the ^{4}He cyclotron frequency, ω_{CHe}, we can directly exhaust them from the chaotic field line region.

5. Summary and Discussion

We have proposed an ICRF sustained LHD type p-^{11}B reactor and have been able to show some possibilities of the reactor. Furthermore, we have proposed an active peripheral potential control method and an active ^{4}He ash exhaust scheme.

In p-^{11}B reactor, the electron temperature is so high that the slowing down process by borons is almost comparable with the slowing down process by electrons. Therefore, in eq. (5), we should take into account the slowing down process by borons, and this will lead to the more severe evaluation for Q. In eq. (5), $E_0 = 0$ has been assumed, however, this assumption will be giving an severe evaluation for Q. An reasonable value for E_0 will be the order of T_e, but, the self-consistent distribution function of the proton should be calculated for a more convincing evaluation of Q.

In the present paper, we have dealt with T_e and T_B as the free parameters in calculations. But, T_e and T_B

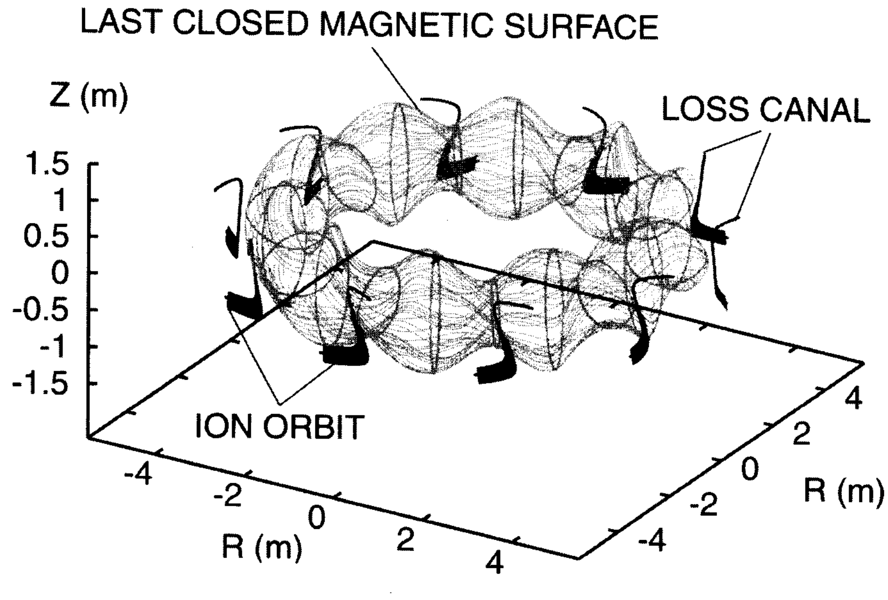

Fig.6 Loss canals in LHD. The orbit of protons lost through the loss canals and the last closed magnetic surface are also shown.

should be evaluated by the energy balance in the reactor. Especially, the synchrotron radiation power loss may become a serious problem in high T_e case. In the LHD type p-^{11}B reactor, however, the magnetic field intensity can be reduced, if we scale up the machine size. There are no limitations for the machine size from the neutron wall loading in p-^{11}B reactor.

In order to realize the economical and steady p-^{11}B reactor, it may be necessary to find another proton heating process. If we take into account the fact of the inverse population of the fusion product ^{4}He and the fact of $\omega_{CH} = 2\omega_{CH}$, we can expect the direct energy transfer from ^{4}He to protons. These works will be carried out in elsewhere.

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References

[1] T. Mutoh *et al.*, Phys. Rev. Lett. **85**, 4530 (2000).
[2] T. Watari *et al.*, *Proc. 18th IAEA Conf. on Fusion Energy* (EX 8/4), 2000, Sorrento.
[3] T.H. Stix., Nucl. Fusion **17** (1975).
[4] J.M. Dawson, *Fusion, vol. 1, Part B* (Academic Press, New York, 1981) p. 453.
[5] H. Ikegami., *Kakuyugo Kenkyu I*, (The University of Nagoya Press, Nagoya, 1996) p. 5 [in Japanese].
[6] H. Momota *et al.*, IPPJ-460, Institute of Plasma Physics, Nagoya, Japan (1980).
[7] R. Feldbacher, INDC(AUS)-12/G, vers. 1 (IAEA International Nuclear Data Comittee, 1987).