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LHD type Proton-Boron Reactor and the Control of its Peripheral Potential Structure

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Abstract

An advanced Large Helical Device (LHD) type proton-boron 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.

I 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 300keV 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 1MeV 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,

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

has the advantages as follows [4][5]:

- Only few neutrons are produced by side reactions at low energy level ($\leq$ 1MeV). So it is not need 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 are 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 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 §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 §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 §4. Section 5 is devoted summary and discussion.

II Possibility of the ICRF sustained 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 ($= P_{RF}/\eta_{RF}$) is needed for the RF oscillator, we can get the net

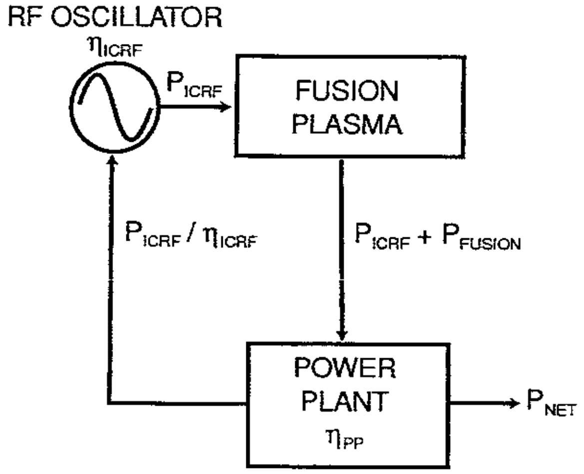

Figure 1: Simplest model of energy flow in the ICRF sustained p-^{11}B fusion reactor plant.

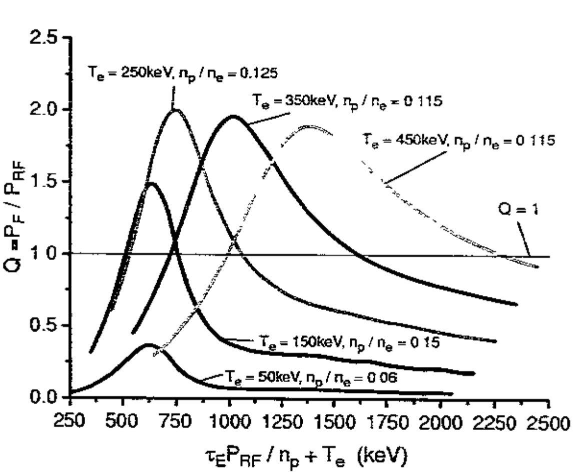

Figure 2: Relationship between Q, P_{RF}, τ_{E}, and T_{e}. $n_{\mathrm{p}}/n_{\mathrm{e}}$ is set to the optimal value for the maximum Q. The line of $Q = 1$ is shown for reference.

output power (=P_{NET}) reduced to

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

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

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

When we substitute reasonable values for $\eta_{\mathrm{PP}}(\simeq 0.5)$ and $\eta_{\mathrm{RF}}(\simeq 0.9)$, 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 ($= n_{\mathrm{e}}$) and temperature ($= T_{\mathrm{e}}$) as:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{P_{\mathrm{RF}}}{n_{\mathrm{p}}} - \frac{E - T_{\mathrm{e}}}{\tau_{\mathrm{E}}}, \qquad (4)$$

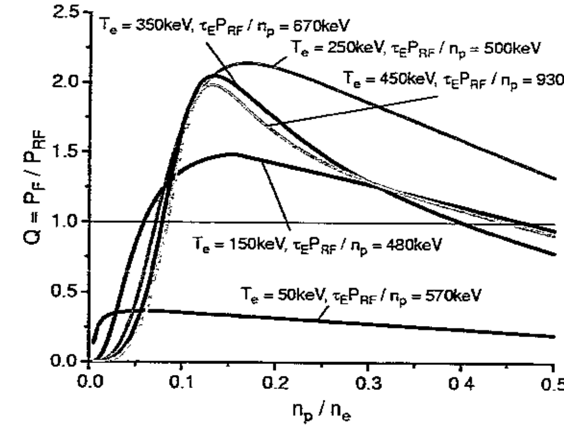

Figure 3: Relationship between Q, $n_{\mathrm{p}}/n_{\mathrm{e}}$, and T_{e} for the case of optimal $\tau_{\mathrm{E}}P_{\mathrm{RF}}/n_{\mathrm{p}}$ values.

reduced to

$$E = E_0 + \left(\frac{\tau_E P_{\mathrm{RF}}}{n_{\mathrm{p}}} + T_{\mathrm{e}} - E_0\right)(1 - e^{-t/\tau_{\mathrm{e}}}), \qquad (5)$$

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 in the following. The value Q becomes

$$Q = \frac{n_{\mathrm{B}}Q_{\mathrm{F}}}{P_{\mathrm{RF}}\,\min(\tau_{\mathrm{b}}, \tau_{\mathrm{f}})} \int_0^{\min(\tau_{\mathrm{b}},\tau_{\mathrm{f}})} \sigma_{\mathrm{pB}}(E)\sqrt{\frac{2E}{M_{\mathrm{p}}}}\mathrm{d}t, \qquad (6)$$

where τ_{b} denotes the time when the bremsstrahlung power loss exceeds the fusion power, τ_{f} represents the time for the nuclear fusion, and M_{p} is the mass of a proton. σ_{pB} denotes the p-^{11}B fusion cross-section [7]. Figure 2 shows the relationship between Q, P_{RF}, τ_{E}, and T_{e}. This figure shows that the optimal ICRF power for the Q value ($\simeq 2$) is nearly equal to $0.32MW/m^3$ when $n_e = 5 \times 10^{20}m^{-3}$, $n_p = n_e/8$ and $T_{\mathrm{e}} = 250keV$. We also show the relationship between Q, $n_{\mathrm{p}}/n_{\mathrm{e}}$, and T_{e} for each optimal P_{RF} values, in Fig. 3, which implies the existence of the optimal $n_{\mathrm{p}}/n_{\mathrm{e}}$. 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.

III 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[8]. 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, numerically by the following

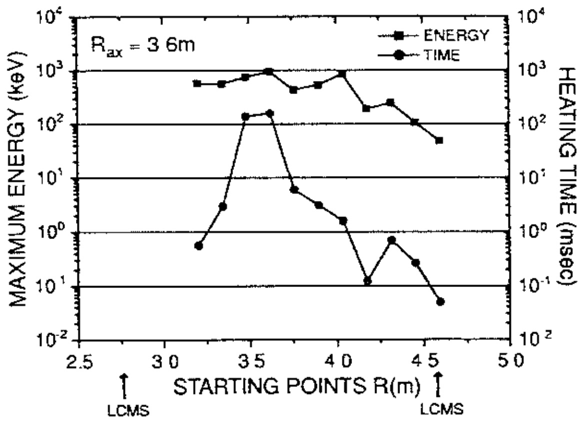

Figure 4: Maximum energy of ICRF heated proton in LHD. $E_0 = 20kV/m$, $m = 0$, $kr = 0$, and $B_{ax} = 2.52T$. The starting points are set on $Z = 0$ plane in the horizontally elongated poloidal crosssection and starting energies are set to 1keV. Heating times to arrive at the maximum energy are also shown.

equation,

$$M\frac{dV}{dt} = e\left[\begin{pmatrix} 0 \\ 0 \\ E_0 \end{pmatrix}\sin(m\phi + k_r r - \omega t) + V \times B\right]$$

with conditions

$$\begin{aligned} E_0 &= 5\,,10\,,20\;kV/m \\ m &= 0, 10, 40 \\ k_r &= 0,\; 38.95m^{-1}\,, \\ \frac{\omega}{2\pi} &= 38.47MHz \\ B_{ax} &= 2.52\;, 2.75\;T\,. \end{aligned}$$

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, the wave number and the electric field intensity of ICRF. The magnetic axis is fixed at $R_{ax} = 3.6$m. Protons are started as passing particles. As shown in Fig. 4, it is found that the average maximum energy of protons becomes order of 1MeV 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 2.9MeV ^{4}He in LHD during 1000 toroidal turns 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).

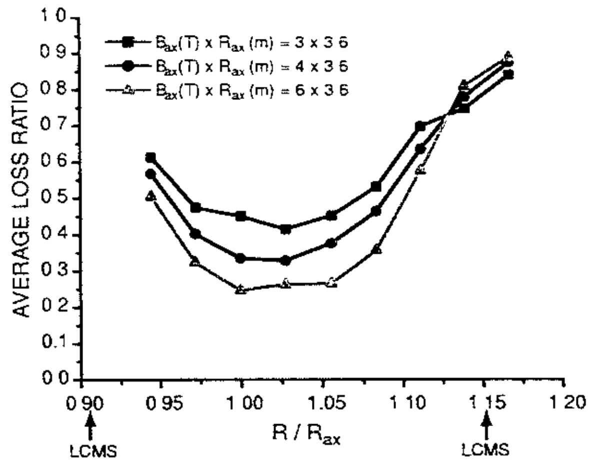

Figure 5: Loss ratio of ^{4}He in the LHD magnetic configuration. Horizontal axis shows the starting points of tracing ^{4}He in vertically elongated poloidal crosssection. R_{ax} denotes the major radius of the magnetic axis. B_{ax} represents the magnetic field intensity on the magnetic axis. The loss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

IV 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 $|\vec{B}| =$ const. plane and $\vec{B} \cdot \nabla B = 0$ 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.

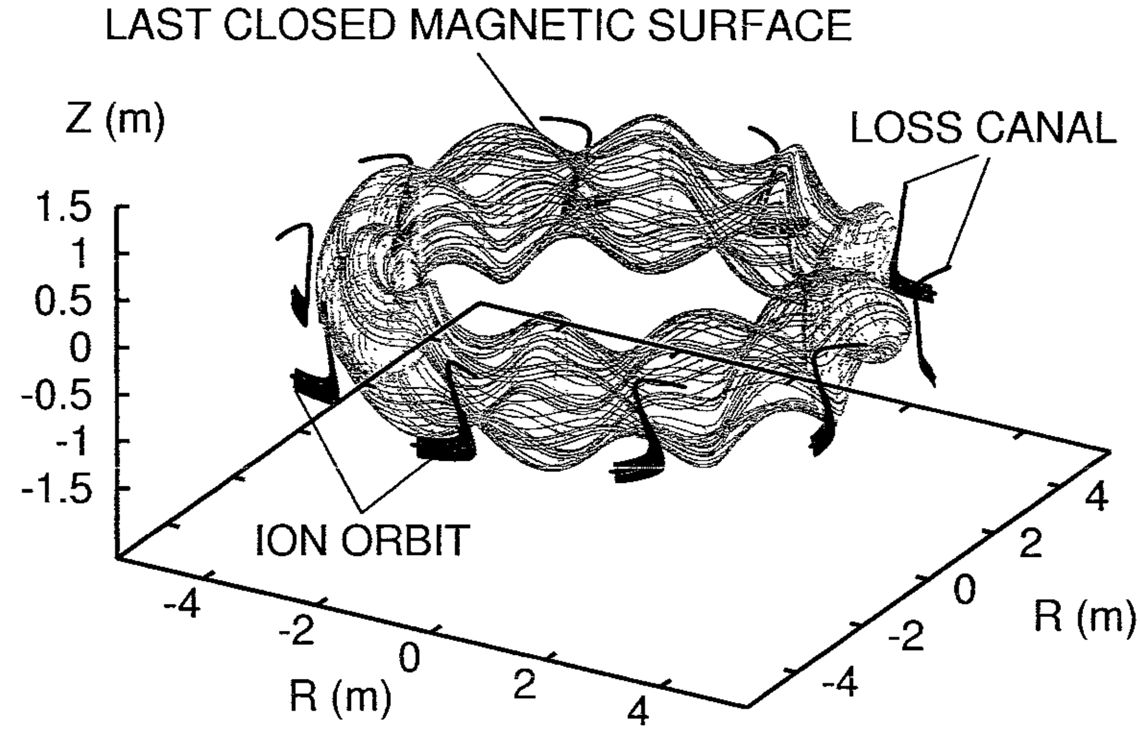

Figure 6: Loss canals in LHD. The orbit of protons lost through the loss canals and the last closed magnetic surface are also shown.

V 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 eq. (5), $E_0 = 0$ have 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 as one of the free parameters in calculations. But, T_e should be evaluated by the energy balance in the reactor. Moreover, 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. Detail energy transport estimation based on the confinement scaling law for LHD will be done in future.

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 $\omega_{\rm CH} = 2\omega_{\rm CHe}$, we can expect the direct energy transfer from ^{4}He to protons. These works will be carried out in elsewhere.

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