Internal transport barrier simulation with pellet injection in tokamak and helical reactor plasmas

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Abstract. In the future fusion reactor, the plasma density peaking is important for the increase in the fusion power gain. The density control and the internal transport barrier (ITB) formation due to the pellet injection have been simulated in tokamak and helical reactors using the toroidal transport linkage code TOTAL. Firstly, the pellet injection simulation is carried out including the neutral gas shielding model and the mass relocation model in the TOTAL code, and the effectiveness of the high field side (HFS) pellet injection is clarified. Secondly, the ITB simulation with the pellet injection is carried out with the confinement improvement model based on the $E\times B$ shear effects, and it is found that the deep pellet penetration is helpful for the ITB formation as well as the plasma core fuelling in the reversed shear tokamak reactor, but the deep pellet penetration is not effective in the helical reactor.

1. Introduction

The total fusion power strongly depends on the radial profile of plasma density, and the density control is important for the fusion reactor operation. To control the plasma density and pressure profiles, the pellet injection is considered as a prospective technique. The pellet injection is used for the plasma core fuelling and for making the density profile peaked. In JET and other tokamak experiments, it was shown that the density profile modifications disagree with pellet ablation theory [1] that assumes the pellet particles remain on the magnetic field lines where they are ionized [2]. The pellet penetration depth measured by the pellet light emission agreed well with the pellet ablation theory. This suggested that a fast outward major-radius drift may occur during the pellet ablation and toroidal symmetrization processes. To test this hypothesis the experiment of the high-field side (HFS) pellet injection has done in ASDEX-Upgrade, and it was shown that the fuelling efficiency and the penetration depth of pellets are improved [3]. The similar results are observed in DIII-D [4] and other tokamak experiments, and the HFS pellet injection is expected to be an effective technique of plasma core fuelling in future tokamak reactors.

When the ITB is formed in the plasma, it brings good confinement and rather peaked pressure profile so that the fusion power gain is increased. The ITB is observed in both tokamak and helical systems and it is classified into several high performance modes, such as high $\beta_p$ mode [5], reversed shear mode [6], and pellet enhanced performance mode (PEP) [7, 8]. Transport simulation studies have been carried out focusing on the ITB formation in tokamak and helical plasmas. In helical systems the ITB model based on Bohm and GyroBohm-like transport with $E\times B$ shear flow effects has
already been compared with the LHD experimental ITB [9] and this model is inspired from the JET mixed-model [10]. This model is introduced into the toroidal transport linkage TOTAL code [11, 12], and is applied to the 1-dimensional (1-D) ITB formation simulation of both 3-D equilibrium helical and 2-D equilibrium tokamak plasmas.

Both the pellet injection and the ITB formation have big influence on the density profile and the fusion power output, so that we investigate the relationship between the ITB formation and the pellet injection density control in tokamak and helical reactor plasmas by using the TOTAL simulation code. Section 2 and 3 will describe the details of the transport models and the HFS pellet injection model included in the TOTAL code, and simulation results will be shown in section 4. The conclusion and discussion will be given in section 5.

2. Transport model description

The Bohm and GyroBohm mixed transport model with the \( \mathbf{E} \times \mathbf{B} \) shear flow effect has already been compared with experimental results of tokamak and helical plasmas with ITBs [9, 10]. The most widely accepted explanation for the ITB formation relies on the suppression of ion temperature gradient (ITG) turbulence due to \( \mathbf{E} \times \mathbf{B} \) shear flow. The suppression of the turbulence might occur when the \( \mathbf{E} \times \mathbf{B} \) flow shearing rate \( \omega_{E \times B} \) exceeds the ITG linear growth rate \( \gamma_{ITG} \). The shearing rate \( \omega_{E \times B} \) is defined as [13, 14]

\[
\omega_{E \times B} \approx \left| \frac{RB_\theta}{B_\phi} \frac{\partial}{\partial r} \left( \frac{E_r}{RB_\theta} \right) \right|,
\]

where \( E_r \), \( B_\theta \) and \( B_\phi \) are the radial electric field, the poloidal and toroidal magnetic field, respectively. In tokamaks, the radial electric field \( E_r \) and poloidal rotation are not easily measured directly, and \( E_r \) is calculated from the plasma radial force balance equation under the assumption that the poloidal velocity can be given according to the neoclassical theory [15, 16]. In this paper, we employ more simple assumption for the \( E_r \) gradient as

\[
\frac{dE_r}{dr} \approx -\frac{1}{en_i^2} \frac{dn_i}{dr} \frac{dp_i}{dr},
\]

in the H-mode condition [17], where \( n_i \) and \( p_i \) are ion density and ion pressure, respectively. In the helical reactor, the radial electric field is determined from the ambipolarity condition of helical ripple-induced neoclassical flux [11].

The ITG growth rate \( \gamma_{ITG} \) is defined as [18]

\[
\gamma_{ITG} = \frac{(\eta_i - 2/3)^{1/2}|s|c_i}{qR},
\]

where \( \eta_i = L_n/L_T \) (\( L_n = d\ln n_i/dr \) and \( L_T = d\ln T_i/dr \)), \( c_i = \sqrt{T_i/m_i} \), \( R \) is major radius, \( q \) is the safety factor, and \( s \) is the magnetic shear defined as

\[
s = q \left( \frac{dq}{dr} \right).
\]
Most of transport simulations adopt a thermal diffusion coefficient $\chi$ in the form

$$\chi = \chi_{\text{neoclassical}} + \chi_{\text{anomalous}} \times F\left(\frac{\omega_{E \times B}}{\gamma_{\text{ITG}}}\right),$$

(5)

where the coefficient $\chi_{\text{neoclassical}}$ is the neoclassical part of thermal diffusion coefficient, and $\chi_{\text{anomalous}}$ is the anomalous part. The effect of the $E \times B$ shear stabilization on the anomalous transport is introduced by an improvement factor $F$. In the present study, we employ the Bohm and GyroBohm mixed transport model [9] of $\chi_{\text{anomalous}}$,

$$\chi_{\text{anomalous}} = 4.0\chi_{\text{Bohm}} + 0.5\chi_{\text{GyroBohm}},$$

(6)

where

$$\chi_{\text{Bohm}} = 4 \times 10^{-5} R \frac{\nabla(n_e T_e)}{n_e B_\phi} q^2,$$

(7)

and

$$\chi_{\text{GyroBohm}} = 5 \times 10^{-6} \sqrt{T_e} \frac{\nabla T_e}{B_\phi^2},$$

(8)

with a simple and widely-used form of $F$

$$F\left(\frac{\omega_{E \times B}}{\gamma_{\text{ITG}}}\right) = \frac{1}{1 + \tau \times \left(\frac{\omega_{E \times B}}{\gamma_{\text{ITG}}}\right)^{\gamma}}.$$

(9)

where $n_e$ and $T_e$ are electron density and electron temperature respectively. In this paper, fitting parameters $\tau$ and $\gamma$ are used with $\tau = 2$, $\gamma = 4$ in tokamak case and $\tau = 15$, $\gamma = 2$ in helical case which were decided from the comparison between the JT-60U and LHD experimental data and the simulation results by using TOTAL code.

3. HFS pellet injection

The high-field-side (HFS) pellet injection is described as two processes which are the pellet ablation and the mass relocation. We simulate the HFS injection with the pellet penetration model combined with the ablation model and the mass relocation model. There are a few models which satisfactorily describe the pellet ablation and relevant experimental light emissions [19]. So, we use here the most popular one; the neutral gas shielding (NGS) model [1] given by

$$\frac{dN}{dt} = 5.2 \times 10^{16} n_e^{0.333} T_e^{1.64} r_p^{1.333} M_i^{-0.333},$$

(10)

where $N$, $n_e$ (m$^{-3}$), $T_e$ (eV), $r_p$ (m), and $M_i$ (u) are the number of particles in a pellet, the electron density, the electron temperature, the pellet size, and the pellet mass, respectively. The number of atoms in the pellet, $N$, is expressed as
\[
N = 2n_s \left( \frac{4\pi r_p^3}{3} \right), \quad (11)
\]

where \( n_s \) is the molecular density of the solid hydrogen (\( n_s = 3.12 \times 10^{28} \text{ m}^{-3} \)). The ablation rate along the pellet path \( l \) is obtained as

\[
\frac{dN}{dl} = 4.38 \times 10^5 N^{0.444} n_e^{0.333} T_e^{1.64} M_i^{-0.333} / V_p, \quad (12)
\]

where \( V_p \) is the pellet injection velocity.

The mass relocation \( \delta x (x = r/a \) is the normalized minor radius) with the plasmoid drift in the major-radius direction is described as [20]

\[
\delta x = \frac{\delta r}{a} - \frac{\delta \psi}{\Delta \psi}, \quad (13)
\]

where \( \psi \) is poloidal flux. The poloidal flux perturbation \( \delta \psi \) scaling is

\[
\delta \psi = q \beta B_p \left( 1 + qL_e / a \right)^{1/2} a^{-1} \delta n_i^2 \left( n + \langle \delta n \rangle \right)^{-1}, \quad (14)
\]

and total poloidal flux within the plasma boundary is

\[
\Delta \psi = \psi(a) - \psi(0) \sim \int r dr / q, \quad (15)
\]

where \( \beta, r_0 \) and \( L_e \) are toroidal beta value, cylindrical cloud with cross-field radius and height, respectively. Figure 1 shows an example of a simulation, where the ablation profile is calculated with the standard NGS model, and that is sifted in the direction to the center by \( \delta x \) calculated with the mass relocation model [20].

![Figure 1](image-url). Schematic diagram of the HFS pellet injection calculation. The ablation profile is calculated with the standard NGS model, and that is sifted in the direction to the center by \( \Delta x \) calculated with the mass relocation model.
4. Simulation results

4.1. Demonstration of HFS pellet injection

The machines parameters of the target tokamak and helical reactors are shown in table 1, which were typical designs optimized using the reactor design system PEC (Physics-Engineering-Cost) code [12]. These parameters refer to the 1GW electric power fusion reactor design. Typical results of the HFS pellet injection simulation in tokamak reactor are shown in figure 2. The size of a deuterium pellet is chosen as \( r_p = 2.5 \text{mm} \). The pellet ablation densities are shown for the different pellet injection velocity \( V_p \). Here, the radial parabolic temperature and flat density profiles are assumed as \( T(x) = T_0(1-x^2)^3 \), \( n(x) = n_0(1-x^2)^{0.5} \) with \( T_0 = 30 \text{keV} \) and \( <n_e> = 10^{20} \text{m}^{-3} \). This figure shows that the HFS injection could provide rather deep fuelling in the reactor-grade tokamak plasma, and the further increase in the injection velocity improves the central fuelling. For assumed temperature and density profiles, the HFS injection with the pellet velocity of 1 km/s could provide the density increase at the normalized radius \( r/a \sim 0.1 \). Moreover, it shows that the reversed shear mode improves the central fuelling for the HFS injection based on the mass relocation model of equation (13).

|                | Tokamak reactor (ITER-like) | Helical reactor (LHD-like) |
|----------------|-----------------------------|---------------------------|
| \( R_p \) [m]  | 5.2                         | 12.5                      |
| \( a_p \) [m]  | 1.2                         | 2.2                       |
| \( \kappa \)   | 2.0                         | -                         |
| \( \delta \)   | 0.5                         | -                         |
| \( B_t \) [T]  | 7.1                         | 4.6                       |

**Table 1. Reactor machine parameters used in this paper**

**Figure 2.** Model prediction for the HFS pellet injection in tokamak reactor. Ablation profiles are shown by a, b and c, and HFS injection simulation results are given by d, e, and f depending on the pellet injection velocities. The profiles d and e are in the normal shear case, and f is in the reversed shear case.
4.2 ITB simulation with pellet injection

In the previous subsection, we show that the pellet injection could provide deep fuelling in tokamak reactor by the HFS injection. So that we compare with deep (by HFS injection) and shallow (by medium field side injection) penetration depth cases in the reversed shear ITB plasmas. The results are shown in figure 3. In the present study, the high pedestal temperature is artificially chosen so that the required fusion power for the 1GW electric power can be obtained. We can see that there are clear differences between both cases. In the deep penetration case shown in the left-hand figure, the large gradient of density and pressure gradients, and the strong reduction of $F(\omega_{E \times B}/\gamma_{ITG})$ defined at equation (9), appear at $r/a \sim 0.5-0.6$, so the ITB is formed. However in the shallow case in the right-hand figure the ITB is not formed.

This reason is shown in the bottom two figures in figure 3. In this simulation, the ITB formation is determined by two parameters, $\omega_{E \times B}$ and $\gamma_{ITG}$. In both cases, $\gamma_{ITG}$ is reduced at $r/a \sim 0.6$ where the magnetic shear $s \sim 0$. The suppression occurs when $\omega_{E \times B}$ exceeds $\gamma_{ITG}$, so the ITB tends to be formed at low $\gamma_{ITG}$ position. However, in the shallow penetration case the rate $\omega_{E \times B}$ is small at $r/a \sim 0.6$, because the gradient of radial electric field $dE_r/dr$ is small depending on the term $dn/dr$ in equation (2). The transient density profile and the relevant clear ITB formation depend on the pellet penetration depth. The deeper pellet penetration brings the larger gradient of $E_r$ and the larger shearing rate $\omega_{E \times B}$ at the position of small $\gamma_{ITG}$, so that the ITB is formed there. We can say that the deep pellet penetration plays an important role in the ITB formation in the model adopted here, and the HFS pellet injection is a quite effective technique for the confinement improvement as well as the core density fuelling in the reversed shear tokamak reactor.

Figure 4 shows the results of the ITB simulation in the helical reactor. It is compared with deep and shallow pellet penetration depth cases (same in tokamak). In this simulation, different from tokamak case, the deep penetration case corresponds to the high speed pellet injection and not to the HFS injection, because the effectiveness of HFS injection has not been observed so far in helical system [21]. This might be because the field connection length between the high filed side and the low filed side is quite short in comparison with tokamak case. In the helical reactor, the radial electric field is determined from the ambipolarity condition of helical ripple-induced neoclassical flux, and the large gradient of radial electric field and strong reduction of $F(\omega_{E \times B}/\gamma_{ITG})$ appear at $r/a < 0.4$ in both cases. In this area flat $q$ profile make small $\gamma_{ITG}$ and the inside gradient of electric field brings large $E \times B$ shear flow, so that the strong reduction in the anomalous transport is occurred. This inside negative electric field is formed autonomously in this reactor grade plasma condition and it seems to be unrelated to the pellet penetration depth. These results show that the deeper penetration is not needed for the ITB formation in the helical reactor.
Figure 3. ITB simulation results with pellet injection in the reversed shear tokamak reactor. Left figures denote deep pellet penetration case (by HFS), and right figures are shallow penetration case (by the medium field side injection). The upper figures (a-1,2) show ion and electron temperatures, electron density, and pellet deposition profiles. The middle figures (b-1,2) show radial electric field derivative and $F(\omega_{\text{ExB}}/\gamma_{\text{ITG}})$ defined at equation (9), and the lower figures (c-1,2) show $\omega_{\text{ExB}}$ and $\gamma_{\text{ITG}}$ profiles.
Figure 4. ITB simulation results with pellet injection in helical reactor. The right-hand figure corresponds to the shallow penetration case (pellet size = 2.5mm, injection velocity = 20 km/s), and the left-hand figure is the deep penetration case (pellet size = 2.5mm, injection velocity = 500 km/s). The upper figures (a-1,2) show ion and electron temperatures, electron density, and pellet deposition profiles. The middle figures (b-1,2) show radial electric field and $F(\omega_{ExB}/\gamma_{ITG})$ which defined at equation (9), and the lower figures (c-1,2) show $\omega_{ExB}$ and $\gamma_{ITG}$ profiles.
5. Summary and discussion
We investigated the relationship between the ITB formation and the pellet injection in tokamak and helical reactors, by means of transport simulation with the TOTAL code. An improvement factor describing the $E \times B$ shear stabilization effect was incorporated to the Bohm and GyroBohm mixed transport model. The high field side (HFS) pellet injection in the tokamak reactor was analyzed and its effectiveness was clarified. In the tokamak reactor with reversed shear profile, it was shown that the pellet penetration depth plays an important role in the ITB formation in the model adopted here, and the HFS injection would be an effective technique for the confinement improvement as well as the plasma core fuelling. In the helical reactor, we showed that the deep pellet penetration is not needed for the ITB formation because the inside structure of radial electric field which makes large $E \times B$ shear flow and strong reduction in anomalous transport is unrelated to the pellet penetration depth. However very high speed pellet injection velocity is required in order to realize the central fuelling. So that, it may be need the other fuelling technique like HFS pellet injection in tokamak about the central fuelling in helical reactor.

These results strongly depend on the transport model and the radial electric field model, and in the present simulation we used semi-empirical transport model with $E \times B$ shear confinement improvement. It should be noted that the large gradient of radial electric field $E_r$ is a key parameter in the present confinement improvement model, and the more accurate $E_r$ modeling different from the present simple model should be adopted in the future.

References
[1] Parks P B and Turnbull R J 1978 Phys. Fluids 21 1735
[2] Bayler L R et al. 1992 Nucl. Fusion 32 2177
[3] Lang P T et al. 1997 Phys. Rev. Lett. 79 1478
[4] Bayler L R et al. 1998 Fusion Technol. 34 425
[5] Koide Y et al. 1994 Plasma Phys. Control. Fusion 36 195
[6] Levinton F M et al. 1995 Phys. Rev. Lett. 75 4417
[7] JET Team (presented by Schmidt G L) 1989 Proc. 12th Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research (Nice, 1988) vol 1 (Vienna: IAEA) p 215
[8] Tubbing B et al. 1991 Nucl. Fusion 31 839
[9] Tala T et al. 2001 Plasma Phys. Control. Fusion 43 507
[10] Garcia J, Yamazaki K, Dies J and Izquierdo J 2006 Phys. Rev. Lett. 96 105007
[11] Yamazaki K and Amano T 1992 Nucl. Fusion 32 633.
[12] Yamazaki K et al. 2006 Fusion Engineering and Design 81 2743
[13] Hahn T S and Burrell K H 1995 Phys. Plasmas 2 1648
[14] Zhou P, Horton W and Sugama H 1999 Phys. Plasmas 6 2503
[15] Ernst D R et al. 2000 Phys. Plasmas 7 615
[16] Kim Y B, Diamond P H and Groebner R J 1991 Phys. Fluids B 3 2050
[17] Hinton F L and Staebler G M 1993 Phys. Fluids B 5 1281
[18] Esposito B et al. 2003 Plasma Phys. Control. Fusion 45 933
[19] Baylor L R et al. 1997 Nucl. Fusion 37 445
[20] Polevoi A R and Shimada M 2001 Plasma Phys. Control. Fusion 43 1525
[21] Sakamoto R et al. 2002 Plasma Phys. Control. Fusion 26B P-1.074