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Plasma Transport Modeling for Tokamak and Helical Systems

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Abstract

The plasma transport code TOTAL (Toroidal Transport Analysis Linkage) is developed to clarify physics properties of both tokamak and helical plasmas. This is composed of one-dimensional transport code with magnetic ripple effects and three-dimensional equilibrium code with bootstrap currents. Ballooning-mode marginal-stable spherical tokamak configurations have been studied and their high beta values are found to be consistent with the normalized beta scaling. However, the engineering beta defined by maximum toroidal field on the plasma surface is found as small as the standard tokamak. The Large Helical Device (LHD) plasmas are also studied using this code, and the bootstrap current is found to make the radial axis-shift smaller, which leads to the decrease in the neoclassical ripple transport loss and the increase in the attainable plasma temperature.

Keywords:

plasma transport simulation, Large Helical Device, spherical tokamak, bootstrap current, NBI heating deposition

1. Introduction

Toroidal confinement system has a great advantage for producing higher plasma performance in tokamak systems, and sustaining longer plasma operation in helical systems. Both confinement properties are quite similar with each other, and it is important to develop a plasma transport modeling code applicable to tokamak, helical and hybrid systems for optimizing toroidal confinement systems.

A new simulation code TOTAL (Toroidal Transport Analysis Linkage) is developed for this purpose using the previous code HSTR [1]. This consists of a three-dimensional equilibrium code with ohmic and bootstrap currents and a one-dimensional transport code with neoclassical and anomalous transport losses. This code is applied to the Large Helical Device (LHD) which had started plasma operation from the end of March in 1998 [2], and to spherical tokamak configurations with ballooning mode stable profiles [3].

2. Model of Transport Simulation

In order to describe two-dimensional (for tokamak) and three-dimensional (for helical system) equilibria, the VMEC code with bootstrap currents [4] are adopted in addition to two-dimensional equilibrium code APOLLO[3], and the helical and toroidal ripple transport losses are studied by taking radial electric field effects into account self-consistently. Especially the multi-helicity field effects on neoclassical ripple transport are included in this code as shown in Ref. [1].

Recently, we have revised the previous code to include impurity transport, bootstrap current and so on.

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The interface to the experimental data has been also added in a new code named as "TOTAL" (Toroidal Transport Analysis Linkage). This is applicable to the simulation prediction and experimental data analysis for both helical and tokamak systems. The flow chart of this analysis code is shown in Fig. 1. The equilibrium is iteratively solved with plasma radial profiles obtained by transport equations or experimental measurements. The details of transport equations adopted here are described in the previous literature [1].

3. Simulation Results

3.1 Tokamak simulation for beta limits

Ballooning mode stable high-beta configurations in spherical tokamak are obtained by using a part of TOTAL code as shown in Fig. 2. This is the typical configuration with central and surface q-values of 1.0 and 3.0, aspect ratio of 1.5, plasma elongation and triangularity of 1.5 and 0.5, respectively. In this case the ballooning-mode marginal-stable toroidal beta value is 22.5%. Here, several beta definitions are used;

$$\beta_t = 2\,\mu_0 \langle p \rangle R / B_t^2,$$
$$4\,\beta_N = 4 I_p(MA)/[a_p(m) B_t(T)]\ (\%),$$
$$\beta = (1/\beta_t + 1/\beta_J)^{-1},$$
$$\beta_{eng} = 2\,\mu_0 \langle p^2 \rangle^{1/2} / [B_{max}(R = R_p - a_p)]^2.$$

Here, poloidal beta value β_J is defined by

$$\beta_J = 4 \langle p \rangle V_p / \mu_0 R I_p^2,$$

with averaged plasma pressure $\langle p \rangle$, plasma volume V_p, major radius R and plasma current I_p. The critical toroidal beta value β_t defined by the central vacuum toroidal field fits well with 4 times of normalized toroidal beta value, $4b_N$, defined with toroidal plasma current I_p, averaged plasma pressure $\langle p \rangle$, plasma minor radius a_p and central toroidal field B_t. However, the total beta value β is as low as 15%. Moreover, the reactor-relevant engineering beta value β_{eng} defined with averaged square pressure and maximum surface toroidal magnetic field is almost independent of aspect ratio. It is concluded that the low aspect ratio configuration has no benefit in increasing the engineering beta value when the maximum field strength is limited by the engineering design of the toroidal coil conductors.

3.2 Helical plasmas without and with bootstrap current

The initial plasma was produced in the LHD (Large Helical Device) experiment on March 31, 1998, with 1.5 T magnetic field strength and typically 100 kW ECH heating power. The typical and preliminary simulation results have been reported in Ref [5].

Recently we have developed our code to include bootstrap current (BSC) self-consistently in the TOTAL code. Figure 3 shows the BSC effects on the magnetic configurations at the central beta value of 3.35%. The rotational transform near plasma center increases dramatically and the radial axis-shift is relaxed. The magnetic well is not stronger than the BSC-free configuration.

Figure 4 shows the simulation results showing BSC effects. In this simulation the anomalous transport is

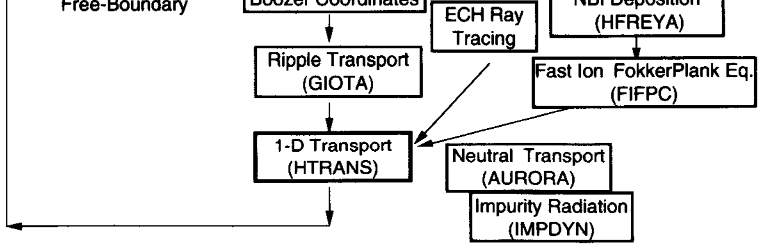

Fig. 1 Flow chart of transport modeling code TOTAL (Toroidal Transport Analysis Linkage).

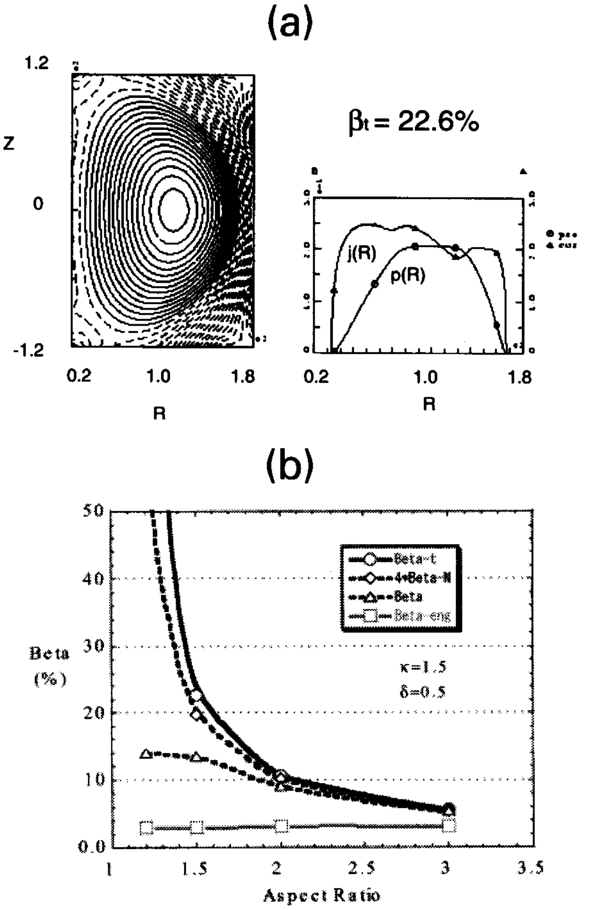

Fig. 2 (a)Typical tokamak configuration marginally stable to ballooning mode in the case of plasma aspect ratio of 1.5, and (b) dependence of beta limits on aspect ratio.

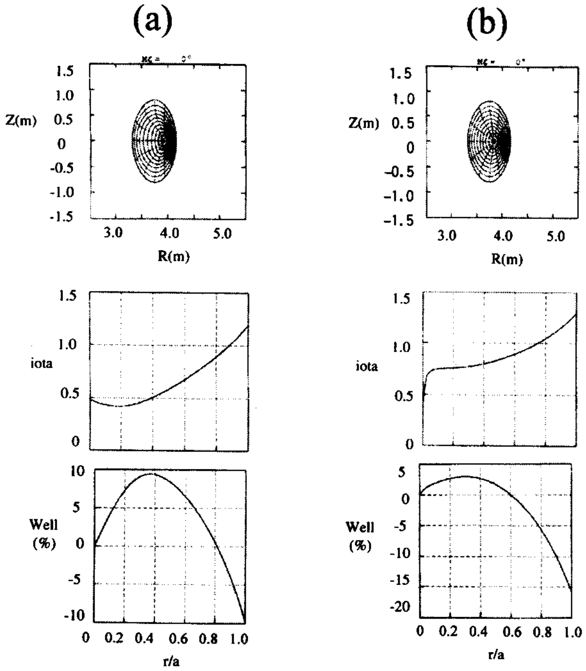

Fig. 3 Effects of bootstrap current on LHD equilibria (a) without and (b) with bootstrap current.

assumed with 2 times of LHD scaling prediction, which is preliminary supported in the LHD experiment [2]. The plasma density profile with BSC becomes less hollow than without BSC, and the radial electric field becomes more negative and the neoclassical ion and electron transport coefficient are reduced by the BSC effect. The finally obtained temperature reaches to ~20% higher value than that of BSC-free plasma. The detailed effects of free-boundary configuration and impurity accumulation are now under investigation.

4. Other Theoretical Analysis Related to Simulation Modeling

The TOTAL code is general toroidal linkage code, but does not cover various kinds of analyses because of the limitation of computer consumption time. In our group, several important analysis are carried out separately, such as three-dimensional MHD stability analysis [6] with CAS3D code, high energy particle heating simulation [7], plasma rotation and H-mode prediction [8], and so on, and some database has been developed for the experimental analysis. The details of each activities are presented in each literature.

Here, the NBI heating simulation analysis is described in Fig. 5. NBI birth profile was calculated by HFREYA code with the 3-D Equilibrium VMEC/NEWBOZ code. The beam slowing down with particle-orbit effects was calculated by the 5-dimensional Monte-Carlo code MCNBI. For 180keV beam, the orbit effect is important in the case of less than 1 Tesla operation. In the case of higher magnetic field than 1.5 T this effect can be neglected as shown in this figure. The conventional analysis without orbit effects used in the TOTAL package is appropriate for higher field. These effects are stored in the simplified database for the LHD experimental analysis

5. Summary and Future Plan

We developed a new code TOTAL consisting of three-dimensional equilibrium and one-dimensional transport code with effects of ambipolar electric field, ripple transport, bootstrap currents, impurities, and experimental data analyzing interfaces. This was applied

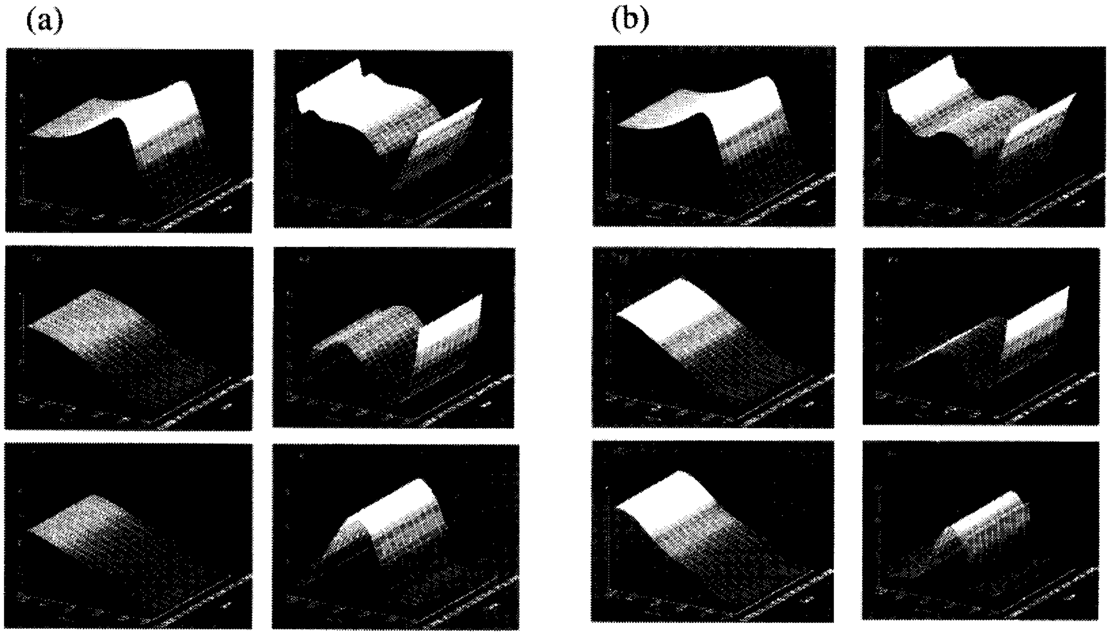

Fig. 4 Transport simulation results for LHD (a) without and (b) with bootstrap current. Radial profiles of plasma density (Ne), electron temperature (Te), ion temperature (Ti), radial electric field (Er) and transport coefficients (Ke, Ki) are shown.

to the spherical tokamak configurations and the LHD experimental plasma analysis. The engineering beta against ballooning mode in spherical tokamak was found as small as the standard configuration. The bootstrap current effect in the LHD was found favorable in the neoclassical ripple transport.

In the near future this code will clarify the confinement comparison between tokamak and helical systems, focusing on magnetic configuration control, radial electric field control, higher beta effect, plasma edge effect and long-pulsed equilibrium relaxation phenomena.

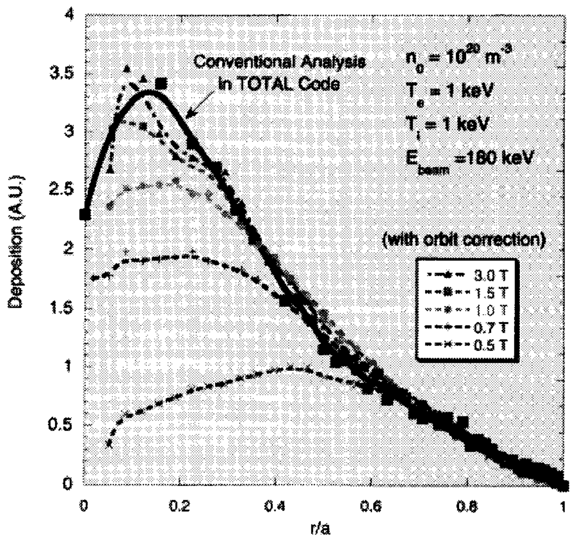

Fig. 5 Power deposition profiles of NBI beam by using (a) the conventional code inside the TOTAL code and (b) the detailed code with orbit effects.

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