Simulations of toroidal rotation driven by the neoclassical toroidal viscosity in tokamaks

M. Honda[1], S. Satake[2], Y. Suzuki[2], G. Matsunaga[1], S. Ide[1], M. Yoshida[1] and N. Hayashi[1]

[1] *Japan Atomic Energy Agency, Naka, Japan*

[2] *National Institute for Fusion Science, Toki, Japan*

Abstract

For simulations of toroidal rotation with the neoclassical toroidal viscosity included, the framework of the collaborative execution of the integrated code TOPICS with the VMEC code and the 3D neoclassical transport code FORTEC-3D has been developed. The contribution of the neoclassical toroidal viscosity to toroidal rotation has been investigated in JT-60SA plasmas.

Introduction

Tokamaks are ideally axisymmetric, but in actual they are not axisymmetric. Due to discrete toroidal field coils, MHD activities, error fields arising from manufacturing and installation errors of coils, perturbed fields applied by error field correction coils and so forth, toroidally-asymmetric components of the magnetic field exist in tokamaks. That is, tokamaks have an inherent 3D nature. It has been found theoretically [1] and experimentally [2] that in tokamaks the neoclassical toroidal viscosity (NTV) that arises from toroidal-symmetry breaking damps or sometimes accelerates toroidal rotation towards a certain rotation level. This is what is called the offset rotation. The NTV and the offset rotation are thus ubiquitous in actual tokamaks. The NTV is, therefore, an indispensable piece of toroidal rotation predictions, but transport simulations with the NTV taken into account have seldom been performed. This is partly because many powerful tools that have been developed for tokamaks explicitly assume axisymmetry and they are not readily applicable to the NTV calculation due to its 3D nature. A drift-kinetic δf Monte Carlo code, FORTEC-3D, which has originally been developed for neoclassical transport analyses in heliotron/stellarator, is able to compute the NTV [3, 4], including effects of the radial electric field E_r in tokamaks [5]. A numerical tool like FORTEC-3D has many advantages in that it does not essentially require a simplified viscosity formula that combines expressions in different asymptotic limits and it can adopt the precise equilibrium and magnetic field without any assumptions.

Methodology

Predicting profiles of toroidal rotation and E_r can be performed by the integrated code, the TOPICS suite [6]. Thus a coupling of TOPICS and FORTEC-3D enables us to calculate a toroidal rotation profile consistent with E_r and the NTV. In this study, first of all, the way of the collaborative execution of both codes has to be firmly established. TOPICS adopts both the geometrical and natural flux coordinates, while FORTEC-3D relies upon the Boozer coordinates, meaning that we have to reconcile the difference of the coordinates. First of all, finite volume modelling of all toroidal field (TF), poloidal field (PF) and central solenoid (CS) coils in a targeted tokamak needs to be prepared for the vacuum field calculation using the COIL code. The code is capable of accurately computing the mean and perturbed vacuum magnetic field vectors that arise from these coil components, based on the Biot-Savart law. A 2D axisymmetric equilibrium computed by TOPICS is reproduced by the VMEC code [7]. Then it is converted to a 3D non-axisymmetric equilibrium that includes the perturbed-magnetic-field effects using the 3D vacuum perturbed fields computed by COIL. The resultant equilibrium includes the response of a plasma to the ripple as well: the ripple of the plasma equilibrium current due to the vacuum ripple [8]. Using the kinetic profiles and the magnetic fields that have been mapped to the Boozer coordinates by the BOOZ_XFORM code, FORTEC-3D solves the drift-kinetic equation time-dependently to obtain the NTV until its mean value reaches a steady state. Due to the Monte Carlo nature, results are more or less fluctuated even in a steady state, so that the time averaging (window averaging) is performed. The calculated NTV profile is given to TOPICS. TOPICS again commences calculating the evolution of the toroidal momentum driven by NTV and, if any, neutral beam injection (NBI) and other sources.

Simulation results

In this paper we confine our attention to the JT-60SA tokamak with 18 TF coils ($n = 18$). The maximum TF ripple on midplane is $\sim 0.7\%$ for a typical equilibrium. Even though the application of the resonant magnetic perturbation (RMP) by error field correction coils will be available, the NTV caused by TF ripple is solely taken into account in our simulation. In the following an advanced inductive scenario of $I_p = 3.5\,\mathrm{MA}$ and $B_T = 2.3\,\mathrm{T}$ is chosen. Applied are co negative-ion-source NBIs of 10 MW, co and counter tangential NBIs of 3.6 MW each, and co and counter perpendicular NBIs of 9.6 MW and 3.2 MW, respectively. The density and temperature profiles are prescribed throughout the simulation, as shown in figure 1 (right), but the toroidal momentum is solved as a dependent variable. E_r is also evaluated at each time step.

Time histories of the toroidal angular momentum, collisional and the $\boldsymbol{j} \times \boldsymbol{B}$ torques due to NBI, which are estimated by the OFMC code, and the NTV torque are shown in figure 1 (left).

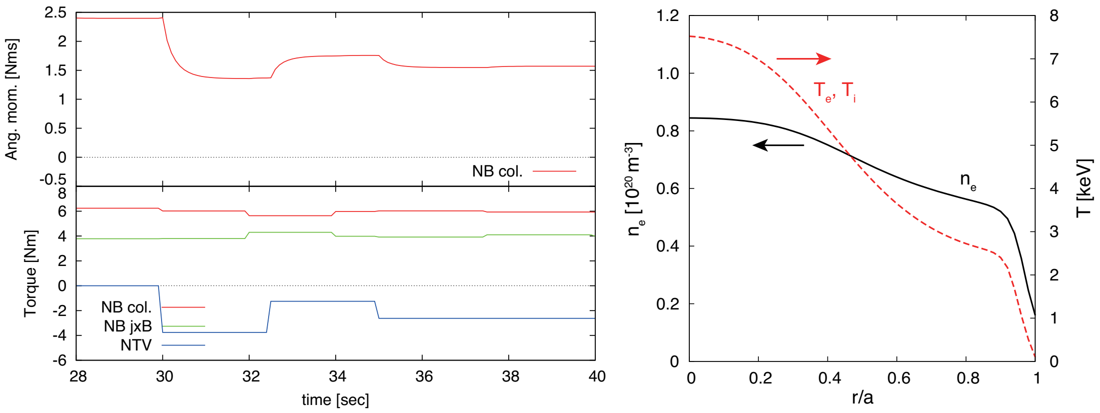

Figure 1: (Left) Time histories of the angular momentum, collisional and the $\boldsymbol{j} \times \boldsymbol{B}$ torques due to NBI and the NTV torque. The NTV torque is firstly applied at 30s, and subsequently at 32.5s and 35s. (Right) Fixed density and temperature profiles.

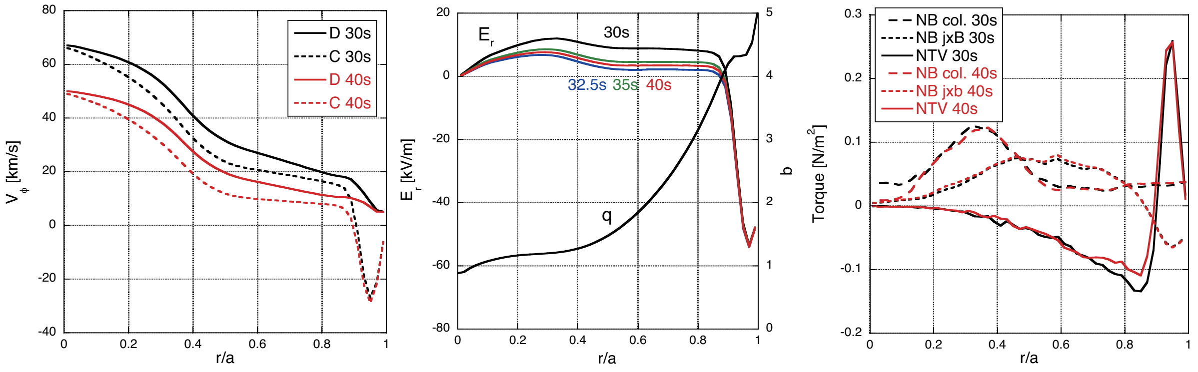

Figure 2: (Left) Toroidal rotation profiles for deuterium and carbon at 30s and 40s. (Middle) The safety factor profile and the evolution of E_r. (Right) Torque profiles at 30s and 40s.

Because of the large computational resource consumption of FORTEC-3D, three iterative calculations between TOPICS and FORTEC-3D were performed. Nevertheless, the toroidal angular momentum almost reaches a steady-state value. In figure 2, profiles of toroidal rotation, E_r, the safety factor, and the torque deposition are shown. Due to the reversal of E_r from positive to negative in $\rho \gtrsim 0.9$, corresponding to the pedestal, the sign of the NTV torque flips as well [5]. Inside the pedestal where the NTV acts as hampering co toroidal rotation, the NTV provides the plasma with the torque almost comparable in magnitude to that by NBI even in the smaller ripple tokamak, JT-60SA. Originally E_r is positive in the core region due to co NBI and the negative NTV is therefore rather large. The negative NTV torque, however, brakes co toroidal rotation and pushes positive E_r towards negative, resulting in the smaller negative NTV. Finally the plasma finds a steady state to balance one another. The resultant toroidal rotation speed is reduced by $\sim 20\,\text{km/s}$ compared to that without the NTV and the difference between them is ascribed to the offset rotation.

The offset rotation is subject to the diamagnetic flow and is proportional to the temperature gradient. The offset rotation frequency is typically given as [9]

$$\langle \Omega_* \rangle \simeq \frac{c_p + c_t}{Z_\text{i} e} \frac{dT_\text{i}}{d\psi}, \tag{1}$$

where c_p is the poloidal coefficient that can be computed using the moment approach, and c_t is the toroidal coefficient that varies according to which 3D effects are dominant [9]. Since the offset rotation and c_p are known, the c_t profile can be readily computed based on (1), as shown in figure 3. c_t overall lies between the two asymptotic collisionality limits: the ν regime of -0.24 and the $1/\nu$ regime of 2.4. This result is consistent with the experimental observation [2], even though in experiments the NTV is due mainly to the $n = 3$ I-coil non-resonant fields. Note that in our simulation any offset rotation models were not employed to predict toroidal rotation: TOPICS simulation with the NTV given by FORTEC-3D as a torque source just gives rise to steady-state toroidal rotation.

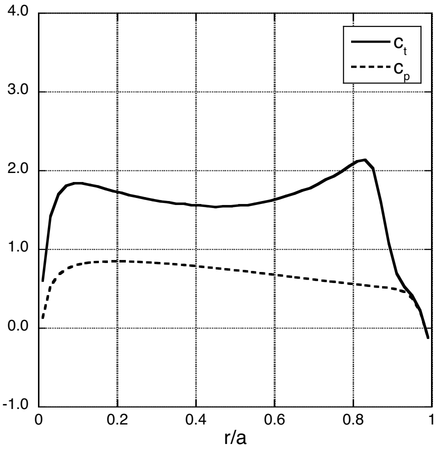

Figure 3: Profiles of the toroidal and poloidal coefficients, c_t and c_p, respectively.

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