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Toroidal rotation modeling with the 3D non-local drift-kinetic code and boundary models for JT-60U analyses and predictive simulations

JT-60U解析と予測シミュレーションのための3次元非局所ドリフト運動論コードと境界条件モデルを用いたトロイダル回転モデリング

Mitsuru Honda, Shinsuke Satake*, Yasuhiro Suzuki*, Maiko Yoshida, Nobuhiko Hayashi, Kensaku Kamiya, Akinobu Matsuyama, Koji Shinohara, Go Matsunaga, Tomoki Nakata, Shunsuke Ide and Hajime Urano

本多充，佐竹真介，鈴木康浩，吉田麻衣子，林伸彦，神谷健作，松山顕之，篠原孝司，松永剛，仲田資季，井手俊介，浦野創

Japan Atomic Energy Agency
801-1, Mukoyama, Naka, Ibaraki 311-0193, Japan
日本原子力研究開発機構　〒311-0193　茨城県那珂市向山801-1
**National Institute for Fusion Science*
322-6, Oroshi-cho, Toki, Gifu 509-5292, Japan
核融合科学研究所　〒509-5292　岐阜県土岐市下石町322-6

The integrated framework for toroidal momentum transport is developed, which self-consistently calculates the neoclassical toroidal viscosity (NTV), the radial electric field E_r and the resultant toroidal rotation V_ϕ together with the scrape-off-layer (SOL) physics-based boundary model. The coupling of three codes, TOPICS, VMEC and FORTEC-3D, makes it possible to calculate the NTV due to the non-axisymmetric perturbed magnetic field caused by toroidal field (TF) coils. It is found that the NTV significantly influences V_ϕ in JT-60U and E_r holds the key to determine the NTV profile. The sensitivity of the V_ϕ profile to the boundary rotation necessitates the boundary condition modeling. Owing to the high-resolution measurement system, the E_r gradient is found to be virtually zero at the separatrix regardless of toroidal rotation velocities. Focusing on E_r, the boundary model of toroidal momentum is developed in conjunction with the SOL/divertor plasma code, D5PM. This modeling realizes self-consistent predictive simulations for operation scenario development in ITER.

1. Integrated modeling with TOPICS, VMEC and FORTEC-3D for the NTV

In present-day tokamaks, there are a variety of torque sources that impart toroidal rotation, like neutral beam injection (NBI) as the primary source. The “intrinsic torque” that is intrinsically generated without external momentum input is expected to be a major momentum source in ITER and a DEMO reactor, and its study is of significant importance. As one of the possible intrinsic torque sources, much attention has been recently paid to the NTV [1], which originates from the 3D non-axisymmetric magnetic field due to the imperfect toroidal symmetry of tokamaks. Enabling us to analyze the NTV in experiments and gain the predictive capability, we develop the cooperative framework among the TOPICS suite, the VMEC 3D equilibrium code and the FORTEC-3D code [2]. Here, TOPICS is the 1.5D integrated transport code and FORTEC-3D is the δf drift-kinetic solver developed originally for 3D devices. VMEC computes a 3D equilibrium with plasma response based on the 2D free-boundary equilibrium computed by TOPICS plus the vacuum magnetic field due to external coils. Coupling of the integrated code suite and the large-scale kinetic code allows us to accurately calculate the complicated NTV without assumptions on a magnetic equilibrium, the collision operator and so forth and to incorporate its effect into interpretive and predictive simulations. For rotation predictions over the entire profile, a boundary condition is as much important as the NTV, whereas a conclusive boundary model for toroidal momentum has not been proposed yet. Focusing on the radial force balance equation between V_ϕ and E_r observed in JT-60U, boundary models are newly proposed with the aid of the SOL/divertor plasma code, D5PM.

2. The NTV torque and its effects on toroidal rotation in JT-60U

JT-60U had the large TF ripple amplitude up to ~2% on the midplane. In the edge region counter-current V_ϕ was observed despite co-tangential NBI, but the radial current torque stemming from a ripple loss of beam ions was not sufficient to fill the rotation gap between simulations and experiments [3]. The NTV calculation for this discharge reveals that the NTV torque, -2.36Nm, is one third as much as the sum of the collisional and radial current torques due to the NBI: 5.99Nm and 0.699Nm, respectively. Figure 1 illustrates the importance of the NTV. Including the NTV largely improves the reproducibility of toroidal rotation. The NTV is typically localized in the outer-core and edge regions and scales as the ripple amplitude increasing towards the edge. E_r also plays a crucial role in the NTV characteristics such as the peak position, direction and amplitude. Correlation between the positions of the NTV peak and $E_r \approx 0$ is clearly observed in Fig.2, due to the trapped particle resonance [4]. It is also found that ferritic steel tiles (FSTs) significantly suppress the up-down asymmetric components of the NTV. Simulations by this framework show some evidence that the NTV is a major player in explaining the different sensitivity of the rotation profile to the ripple amplitude between co and counter rotation cases via E_r. To elucidate a role of the NTV, our cooperative framework is thus applied to a wide variety of JT-60U discharges, such as counter and balanced injection cases with and without the FSTs. This extensive research brings better understanding of the effects of the NTV in JT-60U.

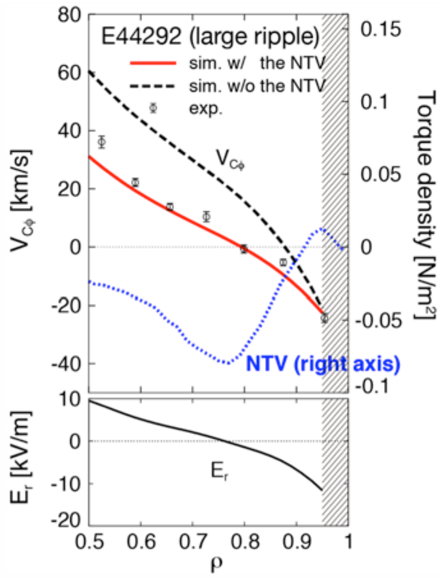

Fig.1. Measured $V_{C\phi}$ profiles and simulated ones with and without the NTV for the JT-60U discharge. The NTV profile (right vertical axis) and the E_r profile are also shown. The boundary is set at ρ =0.95.

3. Modeling of the boundary condition of toroidal momentum for predictive simulations

Despite the importance of the boundary condition (B.C.) for the toroidal momentum density $\langle \mathcal{L} \rangle$, the zero B.C. has prevailed because there are no boundary models. In JT-60U, it was observed that the E_r gradient at the separatrix is independent of V_ϕ and virtually zero [5]. Using this feature, we model the B.C. via E_r: $\langle \mathcal{L} \rangle$ is estimated by satisfying $\nabla E_r = 0$ through the radial force balance equation. The pressure and temperature gradients there are calculated using D5PM. Note that the applicability of the Matrix Inversion method, which is a neoclassical transport solver implemented in TOPICS, in the edge region adjacent to the separatrix has been verified against JT-60U data.

We will predict toroidal rotation over the entire profile for a hydrogen L-mode plasma in ITER. The NTV stemming from the TF coils and the FSTs is taken into account. Co tangential NBs of 33MW are injected. Any profiles other than toroidal rotation are fixed. Predicted rotation at the magnetic axis is up to 2% of Alfven speed, as shown in Fig. 2. Modeling the B.C. and the NTV enables us to perform rotation simulations over the entire profile.

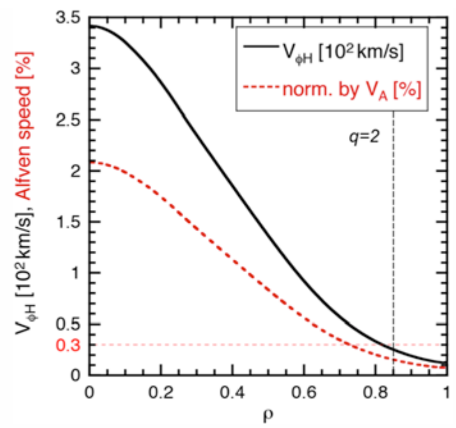

Fig.2. Predicted $V_{H\phi}$ profile in ITER. The red line indicates $V_{H\phi}$ normalized by Alfvén speed.

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