Neoclassical toroidal viscosity from toroidal ripples in JT60-SA

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1. Neoclassical toroidal viscosity in tokamaks

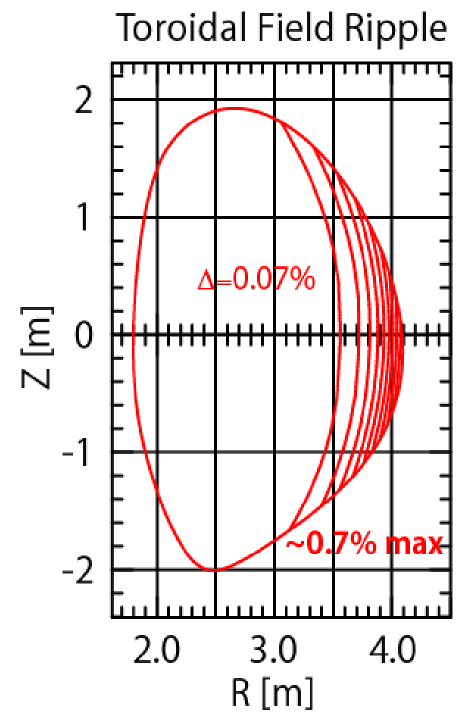
- If a tokamak magnetic field has any broken symmetry in toroidal direction, 3-dimensional effects appears in neoclassical transport phenomena as it is considered in helical plasmas.
- One of the important effects from the incomplete symmetry is the **neoclassical toroidal viscosity** (**NTV**), which decelerate / accelerate plasma toroidal rotation.

$$\left\langle \frac{\partial}{\partial t} mn\mathbf{u}\cdot\mathbf{e}_\zeta \right\rangle = -\underbrace{\left\langle \mathbf{e}_\zeta\cdot\nabla\cdot\overleftrightarrow{\mathbf{P}} \right\rangle}_{\text{NTV}} + \underbrace{\iota\left\langle \mathbf{J}\cdot\nabla\psi \right\rangle}_{J\times B\text{ torque}} + \underbrace{\left\langle \mathbf{e}_\zeta\cdot(\mathbf{F}+\mathbf{S}_m) \right\rangle}_{\text{Friction \& momentum source}}$$

- Recent tokamak experiments have revealed that even very weak asymmetric magnetic perturbation [$\delta B/B_0 = 10^{-3}\sim 10^{-4}$] by RMP (resonant magnetic perturbation) coils can create NTV that damps the toroidal rotation substantially.
- Therefore, accurate calculation method for NTV from weak perturbation is required to predict & control the effect of magnetic perturbations on plasma rotation.

2. Toroidal field ripples in JT-60 SA

- Without external magnetic perturbation, tokamak are not perfectly axisymmetric.
  - ➢ Toroidal field ripples due to discrete toroidal field coils (in JT-60SA case, 18 TF coils)
  - ➢ Error field due to inperfect manufacture or installation of the coils
  - ➢ Iron materials inserted into the vacuum vessels



- Here we consider TF coil ripples in JT-60SA.
  - ➢ 2D MHD equilibrium is first solved by TOPICS code.
  - ➢ Then send the result to VMEC, where finite-β 3D equilibrium with TF coil ripples is solved.
  - ➢ The 3D MHD equilibrium is used to evaluate NTV by FORTEC-3D code.

  - ➢ In an example JT-60SA operation scenario, the relative amplitude of the toroidal ripple is $\sim 0.7\%$.

3. NTV calculation by FORTEC-3D

- FORTEC-3D code solves the drift-kinetic equation for $\delta f = f - f_M$ in 3D magnetic field according to the two-weight δf Monte Carlo method:

$$\frac{D}{Dt}\delta f \equiv \left[\frac{\partial}{\partial t} + (\mathbf{v}_{\|} + \mathbf{v}_d)\cdot\nabla + \dot{\mathcal{K}}\frac{d}{d\mathcal{K}}\right]\delta f - C_{TP}(\delta f) = -\left[\mathbf{v}_d\cdot\nabla + \dot{\mathcal{K}}\frac{d}{d\mathcal{K}} - \mathcal{P}\right] f_M.$$

- Then the pressure tensor and NTV are directly evaluated from the perturbed distribution function δf :

$$\overleftrightarrow{\mathbf{P}} = p_0(\psi)\overleftrightarrow{\mathbf{I}} + \delta P_{\|}\mathbf{bb} + \delta P_{\perp}(\overleftrightarrow{\mathbf{I}} - \mathbf{bb}),$$

$$\left\langle \mathbf{e}_\zeta \cdot \nabla \cdot \overleftrightarrow{\mathbf{P}} \right\rangle = \frac{1}{2}\left\langle \frac{\partial}{\partial\zeta}\delta P \right\rangle, \quad \delta P = \delta P_{\|} + \delta P_{\perp} = m\int d^3v(v_{\|}^2/2 + v_{\perp}^2)\delta f.$$

- Instead of evaluating $\partial P/\partial\zeta$ directly, we make use of the fact that the magnetic field B in FORTEC-3D is given in Fourier series in Boozer coordinates.

$$B(\psi,\theta,\zeta) = B_0\left[1 - \sum_{m\geq 1}\epsilon_m(\psi)\cos(m\theta) + \sum_{m\geq 0, n\neq 0}\delta_{m,n}(\psi)\cos(m\theta - n\zeta)\right]$$

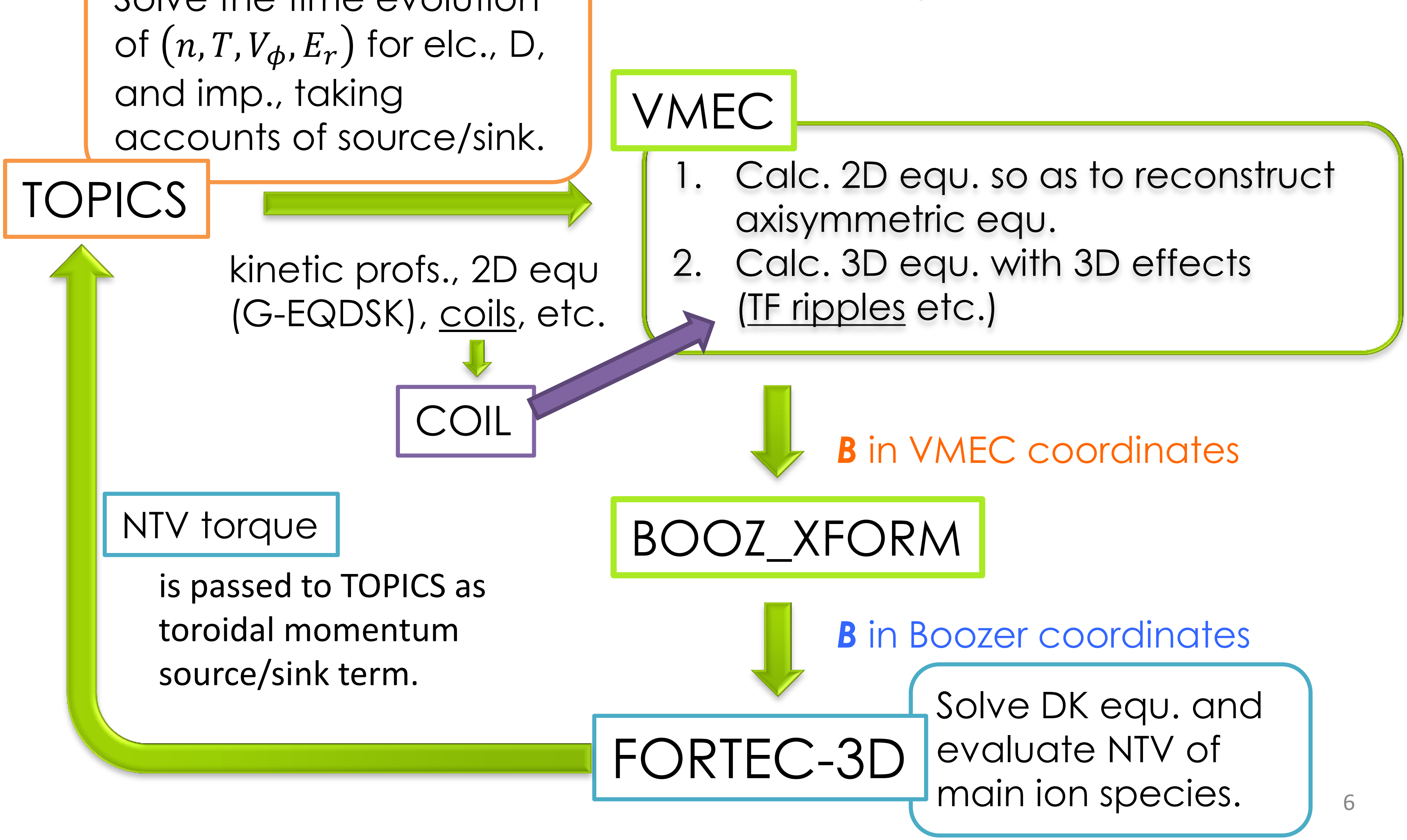
The toroidal viscosity is evaluated by Fourier decomposition in the following form:

$$\boxed{\begin{gathered}\left\langle \mathbf{e}_\zeta \cdot \nabla \cdot \overleftrightarrow{\mathbf{P}} \right\rangle = \sum_{m,n}\left\langle \mathbf{e}_\zeta \cdot \nabla \cdot \overleftrightarrow{\mathbf{P}} \right\rangle_{m,n} = B_0\sum_{m,n} n\delta_{m,n}Q_{m,n}\ . \\ \text{where}\quad Q_{m,n} \equiv \left\langle \frac{\delta P}{B}\sin(m\theta - n\zeta)\right\rangle .\end{gathered}}$$

(Note that present FORTEC-3D can treat only up-down symmetric tokamak configuration.)

4. Combined simulation model for toroidal rotation by TOPICS/VMEC/FORTEC-3D

(figures from M. Honda, EPS 2013)

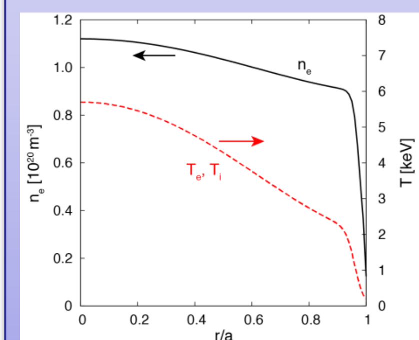


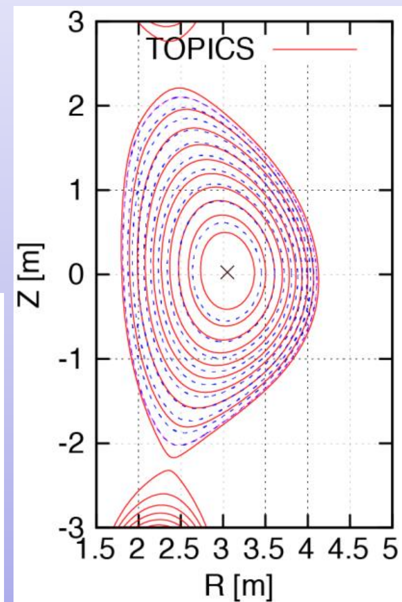
6. Demonstration in a JT-60SA configuration

- Initial setup is calculated by TOPICS code as shown in the figure.
- NBI 30MW: co N-NBI 10MW, co tang 3.6MW, ctr tang 3.6MW, co perp 9.6MW, ctr perp 3.2MW.
- No RMP is applied.

Double Null 5.5MA

R=2.96m, a=1.17m
κ=1.86, δ=0.403,
I_p=5.5MA, B_T=2.3T,
q_0=0.95, q_{95}=3.0,
β_N=2.54, β_p^{th}=0.480



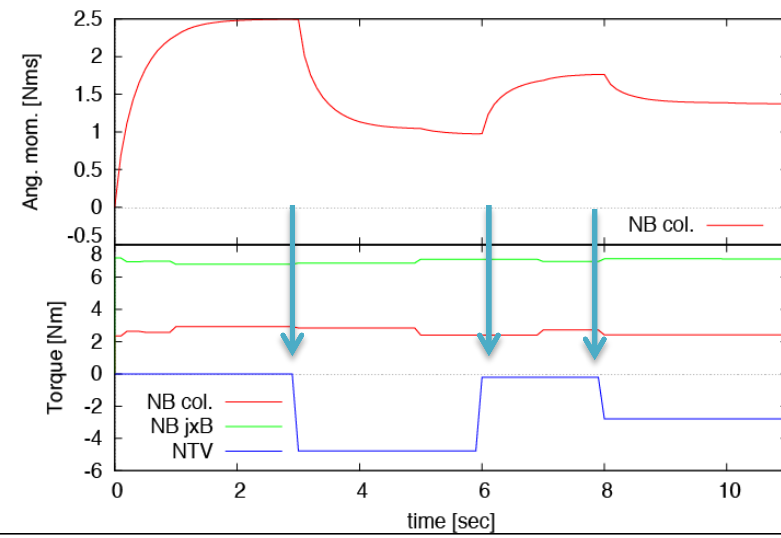


(figures from M. Honda, EPS 2013)

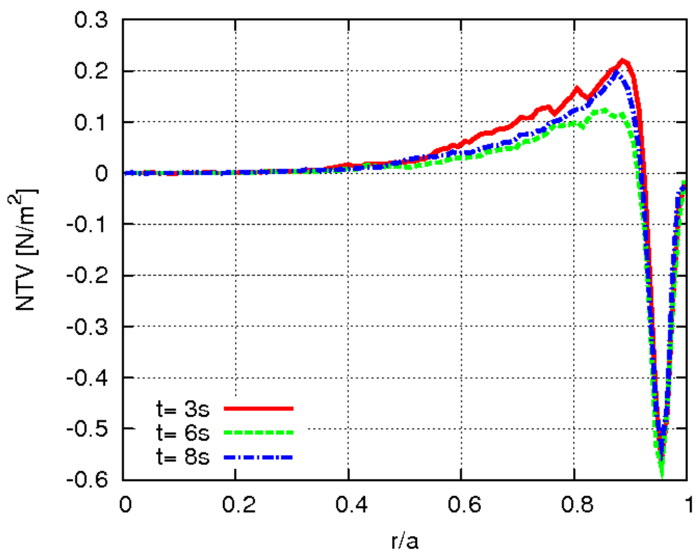
- The radial electric field E_r, which is determined from the toroidal rotation speed V_ϕ and the radial force balance, is sent to FORTEC-3D as input parameters for NC transport simulation as well as n and T profiles.
- Only D ion is considered in FORTEC-3D, and friction b/w Carbon impurity is neglected.
- Iterative simulation between TOPICS and FORTEC-3D is carried out until V_ϕ saturates.
- Single FORTEC-3D simulation takes 15~20 hours on HELIOS using 256 MPIs × 8 SMPs.

Time evolution of toroidal rotation in iterative simulation

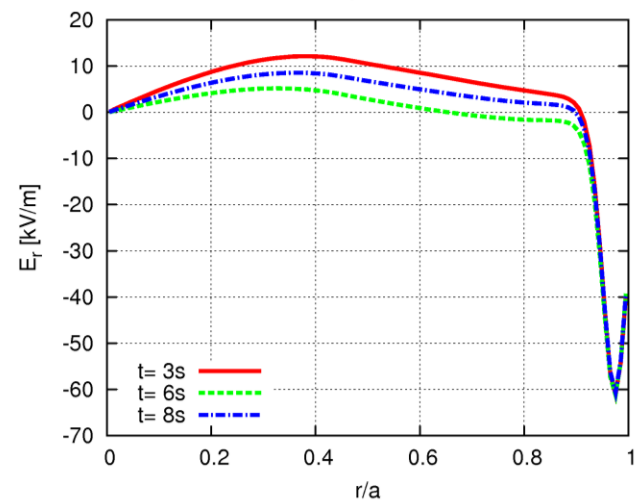
- After 3 times iteration b/w TOPICS and FORTEC-3D, V_ϕ and NTV have reached almost a saturated state.
- E_r and NTV profiles have strong shear at the edge since large pressure gradient exists there.
- Radial force balance (relation among E_r, V_ϕ, and ∇p) determines the E_r profile, and then E_r affects NTV profile.



Time evolution of toroidal angular momentum and given torque input in TOPICS code.



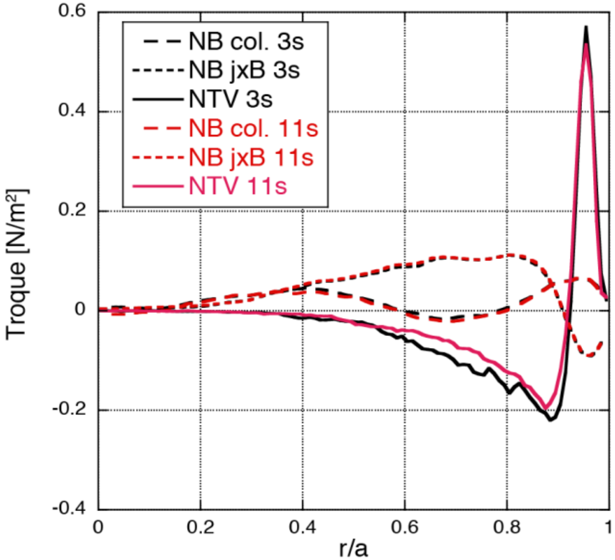
Radial profile of NTV solved by FORTEC-3D for the given $E \times B$ rotation profiles shown in the right figure.



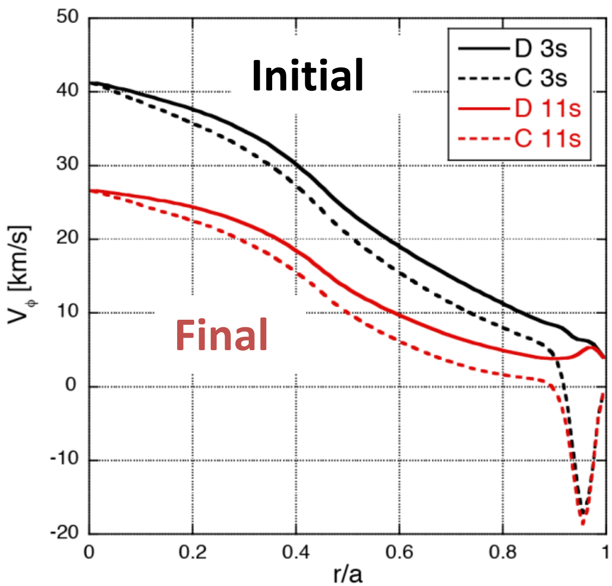
E_r profiles on 3 timings from TOPICS.

Effect of NTV from TF ripples on toroidal rotation

- In the present case, toroidal torque from NTV is comparable to that of NBI.
- NTV torque acts to damp the toroidal rotation driven by NBI.
- The NTV torque on Deuterium damps the bulk plasma rotation. FORTEC-3D does not solve NTV for impurity Carbon, but the Carbon rotation speed also changes in TOPICS as a result of friction between the ion species.



Toroidal torque source / sink from NBI and NTV.



Toroidal rotation speed of D and C ions in the initial state and final state in the simulation.

6. Summary and Future Plan

- It has been demonstrated that the combined simulation model by TOPICS / VMEC / FORTEC-3D can be applied to predict the toroidal rotation profile under the effect of neoclassical toroidal viscosity from TF ripples.

- It is found that the NTV from TF ripples can be comparable to NBI torque and changes the toroidal rotation profile substantially.

- For verification / validation of the combined simulation model, we plan to analyze the experimental observations from previous JT-60U operations before and after the ferritic steel was inserted to reduce the TF ripples.

- To conduct FORTEC-3D simulation for more realistic tokamak configurations, the code is being extended to up-down asymmetric geometry including the effect of external RMPs.