Neoclassical toroidal viscosity induced by resonant magnetic perturbation

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Outline

Introduction

1. The magnetic field in tokamak is designed to be axisymmetric, but in reality, there is always a non-axisymmetric perturbation field due to external perturbations or plasma instabilities, which means $B = B(r, \theta, \phi)$.
2. This perturbation field may strongly affect the plasma rotation profile through the induced neoclassical toroidal viscosity (or NTV) [Shaing 2003], and directly or indirectly, the confinement and instabilities of tokamak plasmas.

Introduction

1. The purpose of this study is to calculate NTV torque induced by plasma response to resonant magnetic field perturbation (RMP) in tokamak edge plasma.
2. The calculation of NTV torque is implemented by using the coupling of NIMROD and NTVTOK.

NTV theory and calculation

1. The perturbation field δB is decomposed into different toroidal and poloidal modes, which can be written as

$$\delta B = B_0 \sum_n b_n(\theta) e^{in\alpha} = B_0 \sum_{n,m} b_{nm} e^{i(m\theta - n\zeta)}$$

$$b_n(\theta) = \sum_m b_{nm} e^{i(m-nq)\theta}$$

2. Bounce averaged linearized dirft kinetic equation

$$I_1 \langle L(f_{1n}) \rangle_b - iI_2 f_{1n} - iI_3 = 0$$

f_{1n} is the perturbed distribution function. After f_{1n} is solved, NTV torque can be obtained using NTV theory.

3. NTVTOK calculates NTV torque based on either one of the following two ways [Sun et al 2010]
    - Analytical solution of BDKE [Shaing 2010].
    - Numerical solution of BDKE.

An initial coupling of NTVTOK and NIMROD

1. Two kinds of parameters are needed in NTV torque calculation, one is tokamak equilibrium parameters, such as pressure, safety factor, collisionality and so on, the other is the non-axisymmetric perturbation field.
2. The perturbation field is advanced by NIMROD code starting from initial tokamak equilibrium based on full MHD model.
3. An initial coupling of NTVTOK and NIMROD is developed, which can be used to calculate NTV torque induced by non-axisymmetric perturbation field in a realistic tokamak configuration.

A simple tokamak equilibrium at low β

Pedestal is located at $\sqrt{\psi_p} \approx 0.7$, $\beta = 0.09\%$

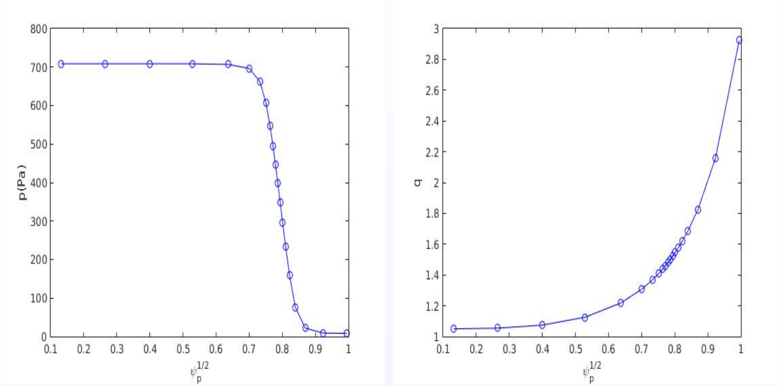


Figure: Pressure and safety factor profile of a real tokamak equilibrium

A simple tokamak equilibrium at low β

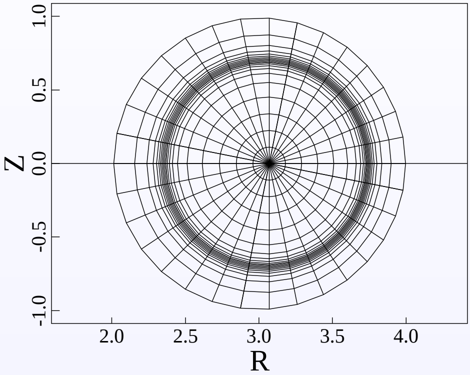


Figure: NIMROD grid based on magnetic surface of low β equilibrium

A toroidal flow is imposed to pedestal region

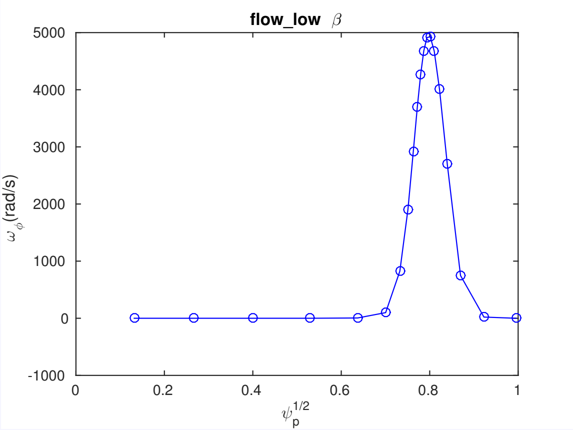


Figure: Mach number of the maximum flow speed is around 0.1.

Nonlinear plasma response calculated using NIMROD ($n = 1$)

The amplitude of RMP is 1.0×10^{-4}, $(m, n) = (2, 1)$

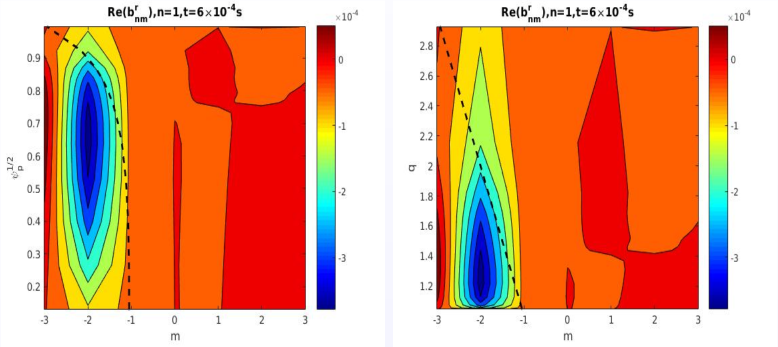


Figure: Contour of $Re(b^r_{nm})$, $n = 1$ on m-$\sqrt{\psi_p}$ and m-q plane. The black dashed line indicates resonant surface [Zhu *et al.* 2015].

NTV torque profile, $T_{NTV} \approx 10^{-13} N/m^2$

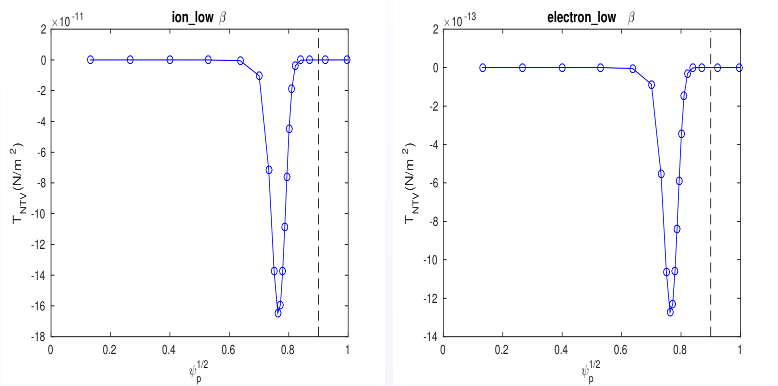


Figure: T_{NTV} profile. The left subfigure shows ions' contribution, the right subfigure shows electrons' contribution.

High β tokamak equilibrium($\beta = 9\%$)

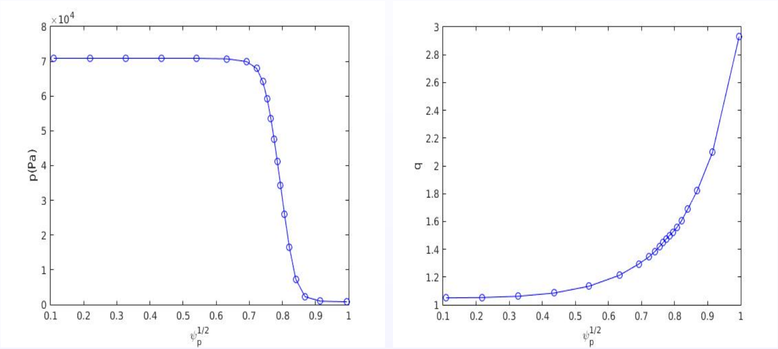


Figure: Profile of pressure and safety factor

High β tokamak equilibrium($\beta = 9\%$)

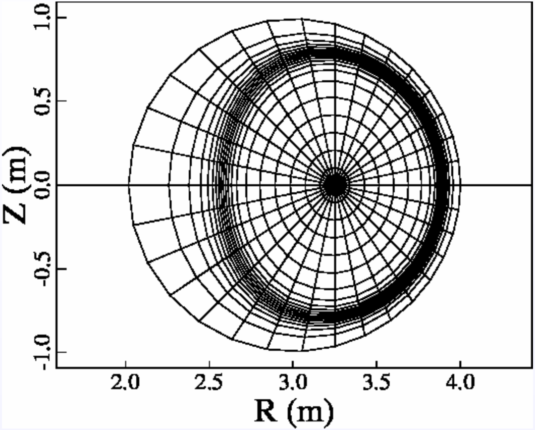
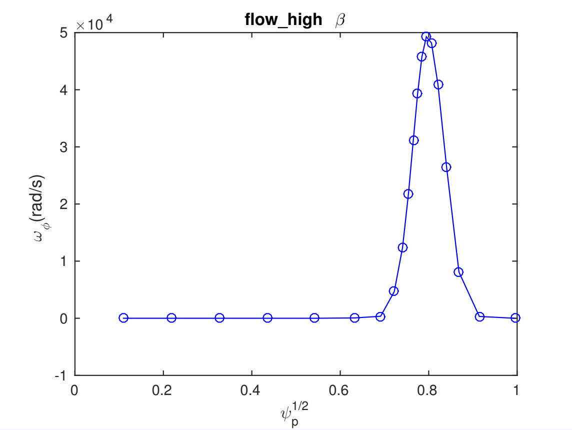


Figure: NIMROD grid based on magnetic surface of high β equilibrium

A toroidal flow is imposed to pedestal region



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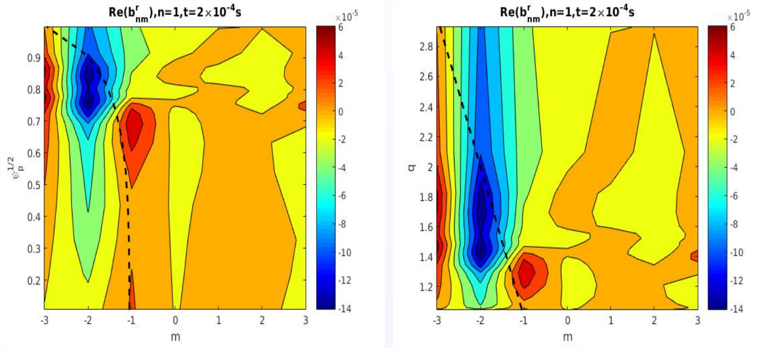

Figure: Contour of $Re(b^r_{nm})$, $n = 1$ on m-$\sqrt{\psi_p}$ and m-q plane. The black dashed line indicates resonant surface [Zhu *et al.* 2015].

NTV torque profile, $T_{NTV} \approx 10^{-2} N/m^2$

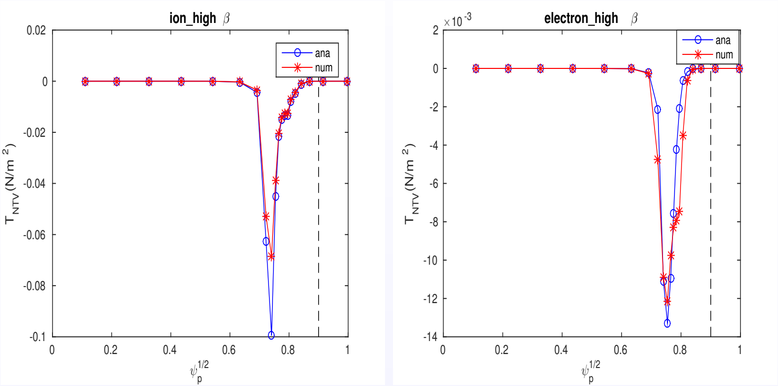

Figure: T_{NTV} profile. The left subfigure shows ions' contribution, the right subfigure shows electrons' contribution.

Nonlinear plasma response calculated using NIMROD ($n = 2$)

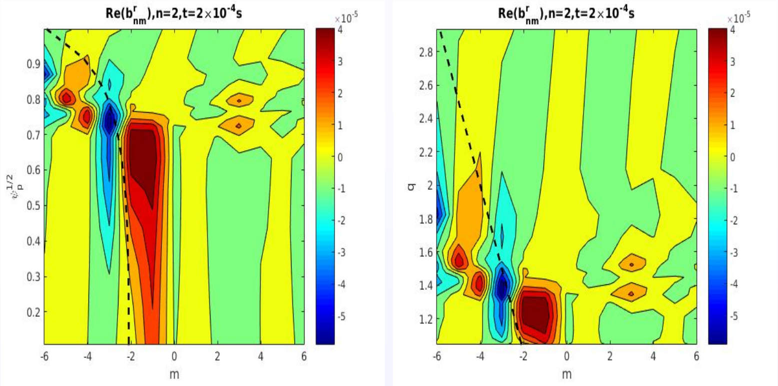

Figure: Contour of $Re(b^r_{nm})$, $n = 2$ on m-$\sqrt{\psi_p}$ and m-q plane. The black dashed line indicates resonant surface [Zhu *et al.* 2015].

The contribution of high n modes to T_{NTV}

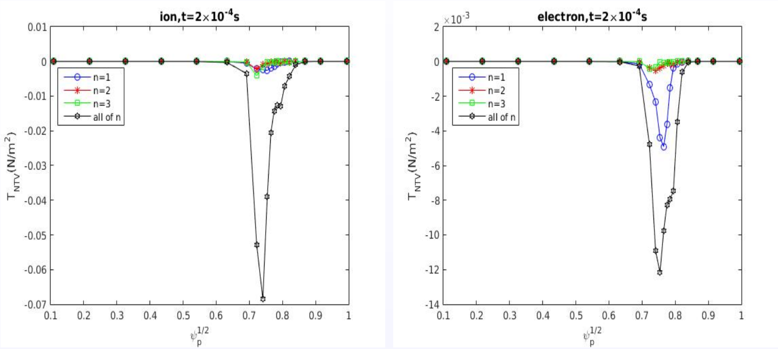

Figure: The contribution of different toroidal modes to T_{NTV}. Blue, red, green and black lines indicate the contribution of $n = 1, 2, 3$ and the sum of all toroidal modes to T_{NTV}, respectively.

Summary

1. An initial coupling of NIMROD and NTVTOK has been developed, which can be used to evaluate NTV torque induced by RMP or instabilities for a realistic tokamak configuration.
2. NTV torque is found to be sensitive to β. When β is increased by 2 orders of magnitude, NTV torque is almost increased by 10 orders of magnitude.
3. High n modes of perturbation field make remarkable contribution to NTV torque, which indicates the importance of nonlinear toroidal coupling effects in NTV calculation.