Test and Validation of TRANSP "Kick"-Model Predictive Capability of Neoclassical Tearing Mode Induced Fast Ion Transport in ITER Relevant DIII-D Plasmas

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I. Introduction

Neoclassical Tearing Modes (NTM) impose a major concern in tokamaks as they can decrease confinement and lead to plasma termination. Energetic particle (EP) - NTM interaction impacts neutral beam (NB) torque, heating and current drive (j_{NB}). This effect has been mimicked in transport codes by an ad-hoc beam diffusivity (χ_{AB}) which broadens the NB profiles. However, the EP response to NTMs depends on the location and width of wave-particle resonances in phase space, whose description requires a physics based model. The TRANSP-"Kick" reduced transport model[1] was developed for Alfvén Eigenmode (AE) driven EP transport, offering a path toward studying NTM-EP interaction. We report the extension of this model to include NTMs by integrating it with a new analysis tool of island structure determination[2] for the first time. Initial tests with ITER baseline, hybrid and ITER steady state discharges in DIII-D are encouraging as this model quantitatively predicts measured neutron rates ($N_\circ$) without free parameters. This model retains all TRANSP functionality and self-consistently predicts the NTM impact on NB torque, j_{NB} and heating. EP transport is significant when phase space resonances overlap, resulting in a transport threshold at W $\approx$ 5cm full island width. This model also shows that the effect on NB profiles strongly depends on the NTM mode numbers with the 3/2 (2/1) broadening (peaking) j_{NB} near the plasma magnetic axis.

II. Representation of NTMs in the "Kick"-model

The "Kick"-model uses the guiding center particle following code ORBIT[3]to calculate EP orbits in the perturbed magnetic field and construct the probability matrix $p(E, P_\zeta, \mu_B, \Delta E, \Delta P_\zeta)$ of ΔE energy and ΔP_ζ momentum changes in the E, P_ζ, μ_B (energy, canonical angular moment and magnetic moment, respectively) phase space. Next, p is used in TRANSP's NUBEAM module to modify the EP distribution. NTMs are implemented through the $\Psi = \Psi_\circ(t)\Psi(\psi)\Psi(\xi(t))$ flux of a 3-dimensional helical current filament running along the O-line of the islands (ψ is the normalized poloidal flux surface label, ξ is the helical angle and t is time). $\Psi(\psi)$ is the solution of Ampere's law for a radial Gaussian current sheet and $\Psi(\xi(t)) = \cos(\xi(t))$ with $\xi(t) = m\theta - n\phi + \omega t$ gives rise to the helical structure with m and n mode numbers and rotating with ω lab frequency (θ and ϕ are the poloidal and toroidal angles, respectively). The amplitude[4] is evolved as $\Psi_\circ(t) = \frac{W(t)^2 B_\theta(\psi_s)}{4L_q(\psi_s)}$ to match to the experimental W. Typical experimental values are $\psi_s = 0.4 - 0.6$, $\omega = 5 - 20$ kHz and $W = 3 - 10$cm, $m/n = 2/1,\ 3/2,\ 4/1\ \&\ 7/2$. The best estimator of $W(t)$ is determined[2] in the experiment in a series of 5 ms windows by fitting the solutions of a heat transport model to phase lock averaged electron temperature (T_e) data [**Fig. 1.** (a,b)]. This gives $W(t)$ when the islands are large and when T_e is available. $W(t)$ is then extended by mapping the magnetic data as $W(t) = \alpha B_\theta^2 L_q (r_m/r_s)^{m+1}$ [**Fig. 1.** (c)]. Here α is a geometric fit parameter, B_θ and L_q are the equilibrium poloidal magnetic field and magnetic field shear length at r_s, respectively. r_s (r_m) is the mode rational surface (Mirnov probe) minor radius coordinate. NTM dynamics is prescribed entirely by these measurements.

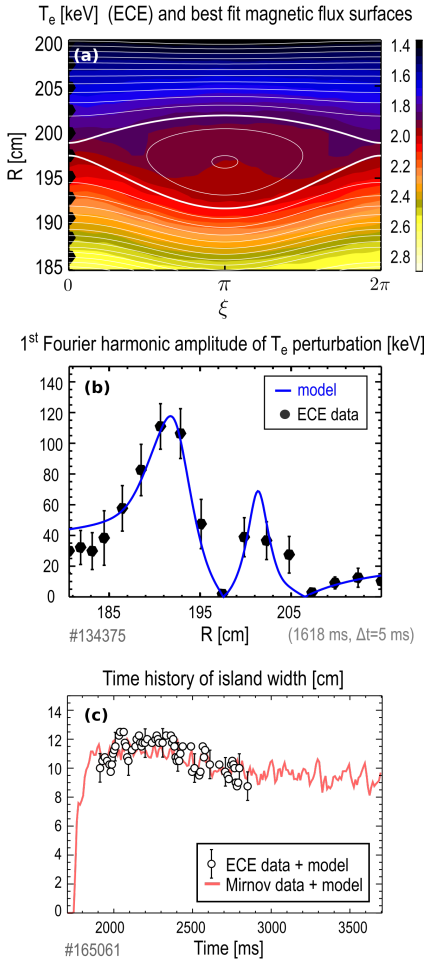

Figure 1: Determination of $W(t)$.

III. Test and validation of the "Kick"-model

Trapped, co- and counter passing ions all strongly interact with the NTM as shown by the energy transfer rate in **Fig. 2.** (a). This picture is qualitatively similar to AEs but the interaction with NTMs is stronger due to the larger $\Psi_\circ$. Resonances occur[5] where $\frac{\Delta\phi - \omega\Delta t/n}{\Delta\theta} = \frac{m'}{nl}$, which give rise to island chains in the EP population with poloidal mode number m', perturbing the NB torque, heat and j_{NB} ($\Delta\phi$ and Δt are integrals on closed orbits and l is any integer).

Initial TRANSP runs of ITER baseline, hybrid and steady state plasmas in DIII-D with the "Kick"-matrix are encouraging with the model quantitatively predicting measured $N_\circ$. The level of transport varies by scenario and W with observed neutron deficits ($\Delta N_\circ$) up to 20% [**Fig. 2.** (d)]. An example of $N_\circ(t)$ is shown in **Fig. 2.** (b), where both the classical and the TRANSP-"Kick" model match the measured $N_\circ$ before NTM onset. The difference between the data and the classical TRANSP result after NTM onset indicates that the EP confinement decreases which is quantitatively captured by the "Kick"-model. In this case $\Delta N_\circ \approx 20\%$ [**Fig. 2.** (c)] when the magnetic amplitude is $\approx$ 10G, and W $\approx$ 10cm.

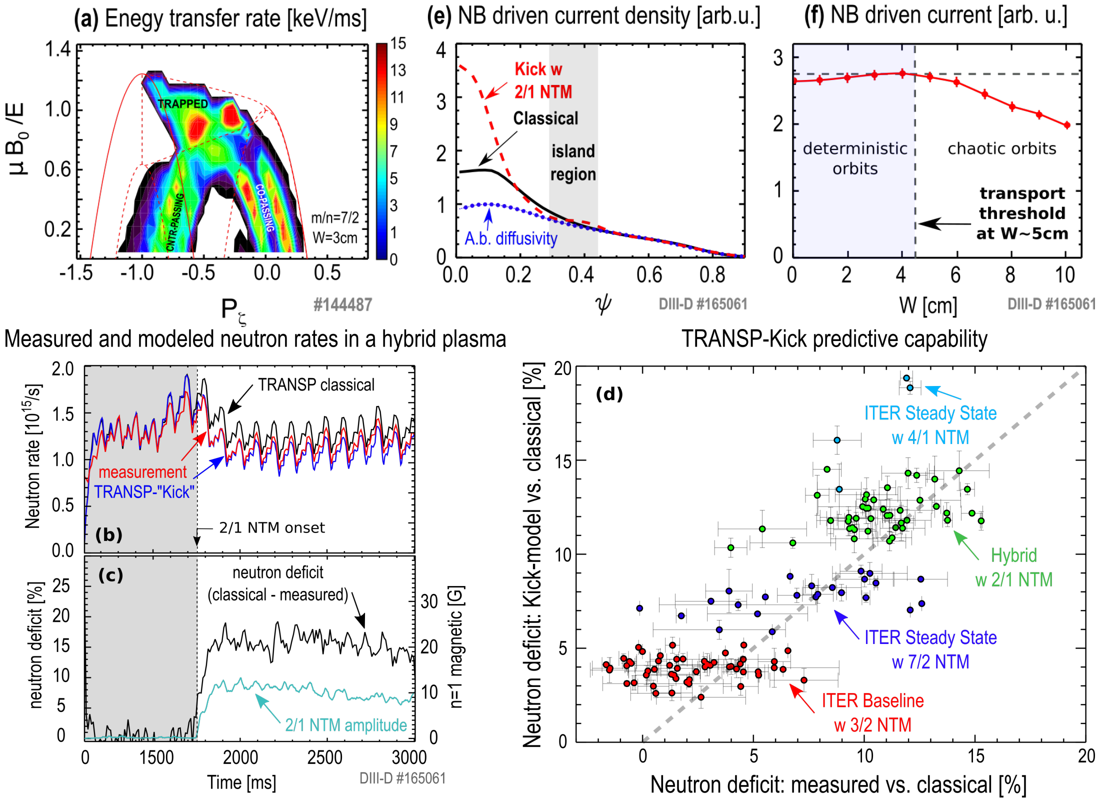

Figure 2: (a) Energy transfer rate between EPs and a magnetic island. (b) Measured and TRANSP $N_\circ$ w & w/o "Kick"-matrix, (c) $\Delta N_\circ$ and NTM amplitude. (d) "Kick" vs measured $\Delta N_\circ$ in a range of discharges. (e) j_{NB} in TRANSP w & w/o "Kick"-matrix and in the χ_{AB} model. (f) Scaling of NB current vs W.

The ad-hoc χ_{AB} model predicts similar electron thermal diffusivity and fast ion (FI) losses when $N_\circ$ are matched. However, the ion thermal diffusivity, core FI pressure, NB driven j_{NB} [**Fig. 2.** (e)] and torque are different. The χ_{AB} model is both quantitatively and qualitatively incorrect. In the "Kick"-model, the island dominantly redistributes j_{NB} in the core as it pushes EP away from the resonance, decreasing (increasing) j_{NB} near (outside) the resonance. In contrast, the χ_{AB} model simply reduces j_{NB} everywhere in the $\psi \approx 0-0.3$ region. EP confinement decreases only when phase space resonances overlap (islands overlap in real space) starting around $W = 5$cm [**Fig. 2.** (f)], turning the initially deterministic orbits into stochastic orbits.

Finally, we tested the effect of islands with different m/n in a set of runs in the same equilibrium [**Fig. 3.**]. Overlapping resonances of a $W = 5$cm 2/1 magnetic islands result in (i) a chaotic region at $\psi > 0.4$ and (ii) a large $1/1$ island in the EP population at $\psi \approx 0.2$. (i) Reduces j_{NB} in the $0.5 < \psi < 0.8$ region, while (ii) leads to a dip in j_{NB} at the resonance as well as a peak in j_{NB} near the magnetic axis. A $3/2$ NTM also forms overlapping islands in the $\psi > 0.5$ region. However, in contrast to the 2/1 NTM, the 3/2 NTM forms a $2/1$ island in the EP population in the $\psi < 0.15$ region which leads to a FI current perturbation δj_{NB} that broadens j_{NB} near the axis.

This δj_{NB} may from a magnetic island destroying the nested flux surfaces of the equilibrium in a narrow region near the magnetic axis. This change of core topology could result in an additional loss of thermal confinement and current which may be an important mechanism keeping the safety factor above 1 on axis of hybrid plasmas. However, this mechanism is only hypothesized here.

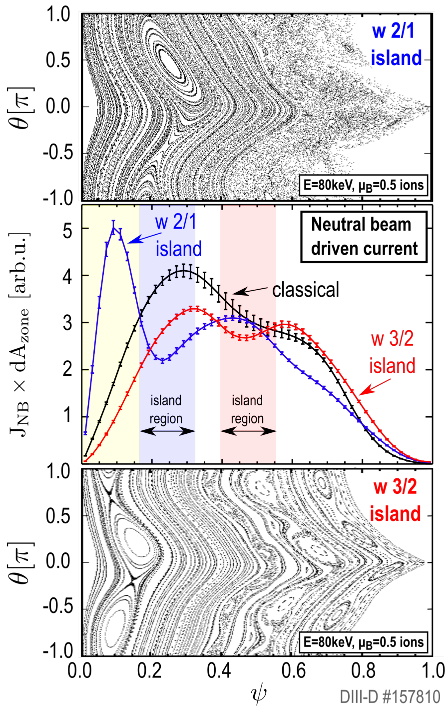

Figure 3: Effect of **(a)** an $m/n = 2/1$ and **(c)** an $m/n = 3/2$ NTM on **(b)** j_{NB}.

IV. Conclusions

We have extended the TRANSP-"Kick" model[1] to include NTM driven EP transport by integrating it with a new analysis tool of island structure determination[2] for the first time. Initial tests with ITER baseline, hybrid and ITER steady state discharges in DIII-D are encouraging as this model quantitatively predicts measured neutron rates ($N_\circ$) without free parameters. EP transport is significant when phase space resonances overlap, resulting in a transport threshold at W $\approx$ 5cm full island width. The effect on NB profiles strongly depends on the NTM mode numbers with the 3/2 (2/1) broadening (peaking) j_{NB} in the core.

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