Simulation of Fast Ion Anomalous Transport in DIII-D

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Introduction

This study deals with current diffusion simulations of DIII-D experiments dedicated to q-profile control during the current ramp-up. For some shots containing Toroidal Alfvén Eigenmodes (TAEs), the experimental evolution of the minimum safety factor q_{min} during the current ramp-up is not well reproduced. It is essential to be able to predict the time evolution of the q profile in order to obtain optimized scenarios (with feedback control of current drive sources for instance) for high fusion gain and steady-state operations with fully non-inductive plasma current.

The discrepancy between experiments and simulations is consistent with a non-inductive off-axis current drive source. This off-axis current source may be due to fast ion anomalous transport, ignored in simulations, leading to an incorrect prediction of the fast ion current drive [1]. The standard formula for neutral beam current drive (NBCD) is given by Eq.1:

$$j_{NBCD} = j_{fast}\left(1 - \frac{Z_{fast}}{Z_{eff}}(1-G)\right), \tag{1}$$

where j_{fast} is the fast ion current density, Z_{fast} and Z_{eff} are the charge of neutral beam fast ions and the effective charge respectively, and G represents the trapped electron correction to the Ohkawa current, whose expression can be found in [2]. Thus, an evaluation of the fast ion current drive without transport may lead to an incorrect prediction of the q-profile. Recent analysis has shown that assuming off-axis NBCD (simulated by an artificial NBCD gaussian current profile centered at the plasma mid-radius), can fit experimental observations [3].

The purpose here is to determine whether this off-axis NBCD can be simulated by quantifying diffusion and convection processes resulting from a possible interaction between fast ions and plasma instabilities. The approach does not adopt a specific theoretical model, but attempts to reproduce experimental data with simple effective diffusion and convection terms, which can be compared with theory.

Procedure

For this purpose, the SPOT/SINBAD package in the CRONOS integrated modeling suite [4] has been used. SINBAD [5] simulates the neutral beam injection and the related ionisation profile. SPOT [6] is an orbit following Monte Carlo code simulating the distribution function of the fast ions in the guiding center approximation and the resulting current drive. In this coupling, SPOT uses the ionisation rate profile calculated by SINBAD as fast ion source. Globally, current diffusion simulations are carried out using the NBCD from the SINBAD/SPOT package and kinetic profiles from the experiment.

The systematic study consists of varying the amount of diffusive and convective transport applied to the fast ions, utilizing a high diffusion coefficient D_{ano} in the plasma centre up to a radius ρ_{cut}, outside which the diffusion coefficient drops toward the edge. A convective velocity v_c, peaked at ρ_{cut}, is quantified as well. The basic profiles used in this model are illustrated in Fig.1. The aim of this study is to find the values of D_{ano}, v_c and ρ_{cut} that best fit the q_{min} evolution during the discharge while being consistent with the estimated fast ion losses (evaluated from the ratio between the experimental and predicted neutron rate).

After a successful benchmark of the SPOT/SINBAD package via comparisons with other simulations and with DIII-D standard L-mode shots (see Fig.2 as an illustration of this benchmark), an analysis of discharges for which Alfvén eigenmode activity has been diagnosed (according to fluctuations observed on the spectrum of measured density), has been carried out. For these shots, a discrepancy is found between the experimental time evolution of the minimum safety factor q_{min} and the simulated one, which displays a faster decay. These differences may be interpreted as an inaccurate modeling of the fast ion current profile, maybe due to the missing fast ion anomalous transport in the simulations, which would lead to a shift of the NBCD toward the edge. Hence, a simple radial transport operator has been added into SPOT, in order to quantify this possible anomalous transport, as shown in Eq.2:

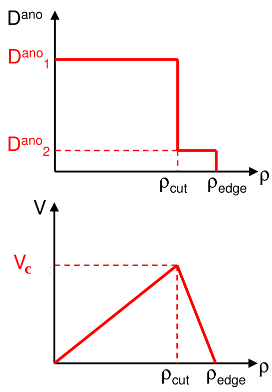

Figure 1: *Simplified shape of the ad-hoc diffusion coefficient and convection velocity profiles.*

$$\Delta\Psi = \left[\frac{1}{\sqrt{g}}\frac{\partial}{\partial\Psi}\left(\sqrt{g}D_{ano}^{\Psi\Psi}\right) + v_c^{\Psi\Psi}\right] N_{acc}\Delta t + \xi\sqrt{2D_{ano}^{\Psi\Psi}N_{acc}\Delta t}, \quad (2)$$

where $\sqrt{g}$ is the jacobian of the coordinate transformation, Ψ is the poloidal magnetic flux coordinate, $D_{ano}^{\Psi\Psi}$ and $v_c^{\Psi\Psi}$ are the the diffusion coefficient and convection velocity respectively, both expressed as a function of the Ψ coordinate, Δt is the integration time step, ξ is a random number with a zero mean and unit variance, uniformly distributed in the range $[-\sqrt{3}, \sqrt{3}]$, N_{acc} is the factor related to the acceleration of the Monte Carlo operators (i.e. one simulated orbit represents N_{acc} orbits in reality), and $\Delta\Psi$ the radial transport of fast ions induced by the plasma turbulence. Usually, the diffusion coefficient and the convection velocity are expressed as a function of the plasma minor radius coordinate r rather than the Ψ coordinate: in the approximation of a plasma circular geometry, one can consider $D_{ano}^{\Psi\Psi} \simeq D_{ano}^{rr}\left(\frac{\partial\Psi}{\partial r}\right)^2$ and $v_c^{\Psi\Psi} \simeq v_c^{rr}\left(\frac{\partial\Psi}{\partial r}\right)$ (notation: $D_{ano} = D_{ano}^{rr}$ and $v_c = v_c^{rr}$).

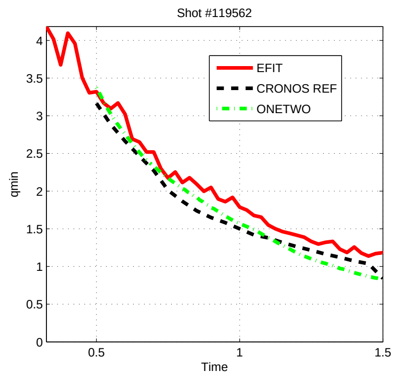

Figure 2: *CRONOS and ONETWO simulations of the minimum safety factor* q_{min} *evolution compared to the experiment for shot #119562.*

Results

This simple model has been applied to some H-mode discharges for which Alfvén eigenmode activity has been identified: shots #123042 and #122681. For these shots, classical simulations without fast ion anomalous transport do not reproduce the experimental q_{min} time evolution (this disagreement stands using the ONETWO transport code as well).

Several sets of values for anomalous transport quantities D_{ano1}, D_{ano2}, v_c, and ρ_{cut} have been investigated, leading to a consequent shift of the NBCD outwards, modifying the time evolution of q_{min} accordingly. These combinations have been chosen so that the fast ion losses do not exceed the one evaluated by the comparison between the experimental and predicted neutron rates. For both shots, fast ion losses are estimated to be around 20%. These combinations are exposed in Tab.1 and the resulting q_{min} evolution are displayed in Fig.3.

	D_{ano1}	D_{ano2}	ρ_{cut}	v_c
Test 1	2.2	0.6	0.5	0.4
Test 2	1.4	0.3	0.3	1
Test 3	2.8	0	0.5	1.6
Test 4	0.6	0	0.5	0.8
Test 5	1.5	0.3	0.4	1

Table 1: *Values of anomalous transport coefficients for the five tests carried out with the SPOT code (D_{ano1} and D_{ano2} are in m^2/s,v_c is in m/s and ρ_{cut} is dimensionless).*

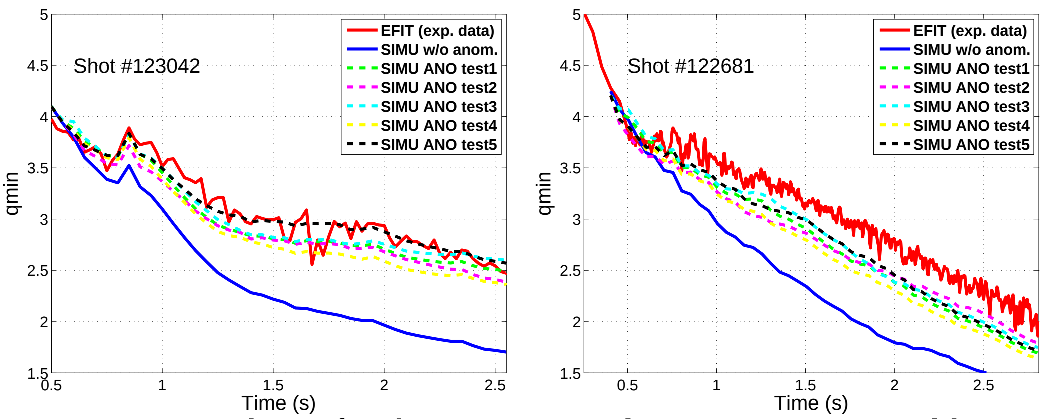

Figure 3: q_{min} *time evolution for shots #123042 and #122681, as measured by EFIT and simulated by CRONOS, first without fast ion anomalous transport, then with the five sets of anomalous transport coefficients tested.*

As can be seen, the combination which best fits the experimental results is the one of test 5, i.e. with $D_{ano1} = 1.5\ m^2/s$, $D_{ano2} = 0.3\ m^2/s$, $\rho_{cut} = 0.4$ and $v_c = 1\ m/s$. The resulting q-profile is shown in Fig.4 for shot #123042 at t=2s for comparison with the experimental q-profile and the one obtained by CRONOS simulations without anomalous transport. As can be seen, the q-profile with anomalous transport fits the experimental q-profile much better than without anomalous transport. Fig. 3 shows a better agreement for shot #123042 than #122681. This may be due to the weak Alfvén activity observed in shot #122681, meaning that the discrepancy in its q_{min} time evolution is not directly correlated with a redistribution of the

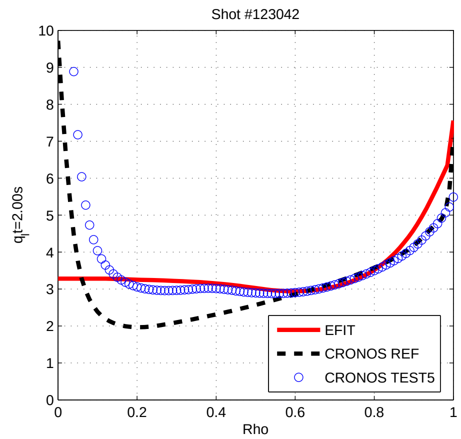

Figure 4: *Experimental and simulated q-profiles for shot #123042 at t=2s.*

fast ion tail. The associated NBI and total current profiles are shown in Fig.5 for shot #123042, along with reference NBI and total current profiles (i.e. without anomalous transport) and the experimental plasma current profile. As can be seen, the experimental current profile is well reproduced by simulations when anomalous transport is included, emphasizing a strong fast ion redistribution, probably due to interaction with TAEs.

Summary and prospects

In some DIII-D H-mode discharges, for which an Alfvén eigenmode activity has been detected, the experimental plasma current profile is not well reproduced by simulations: the simulated q_{min} decay is much faster than the experimental one. An agreement can be established when fast ion anomalous transport is assumed, shifting the fast ion current profile off-axis. Different combinations of diffusion coefficient and convection velocity have been tested with the SPOT Monte Carlo code in order to reproduce the experimental measurements. The best combination, fitting the measurements of the two analysed shots, according to the model of Fig.1, is with $D_{ano1} = 1.5\ m^2/s$, $D_{ano2} = 0.3\ m^2/s$, $\rho_{cut} = 0.4$ and $v_c = 1\ m/s$. These anomalous diffusion coefficients are of the same order of magnitude as those used in [7] to reproduce DIII-D shots exhibiting an MHD activity (in [7], D_{ano} is $1 m^2/s$ at the centre and $\simeq 0.15 m^2/s$ at the edge). However no convection velocity was assumed in [7], but if the convection is removed from the present simulations, it becomes more difficult to obtain a good match with experimental measurements. This seems to indicate the presence of an MHD-induced radial convective transport of fast ions. The next step will be to simulate other DIII-D shots containing TAEs in order to know if this magnitude of anomalous diffusion and convection stands. If so, this could be a valuable indication for further theoretical investigations of the interaction between fast ions and TAEs.

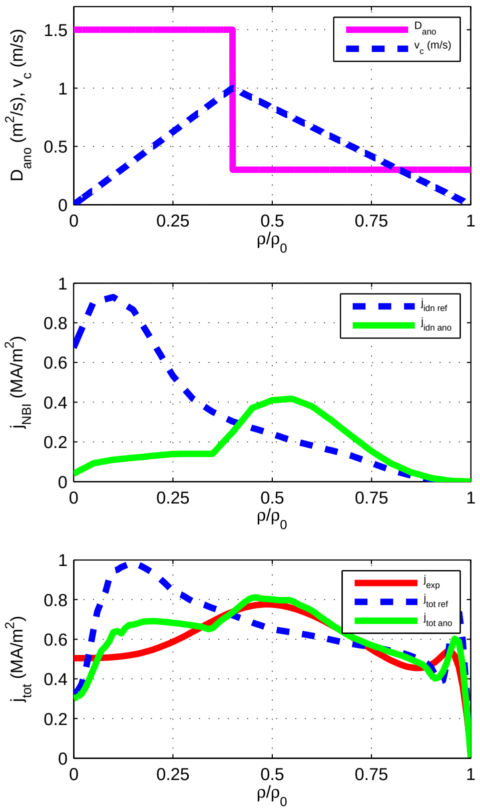

Figure 5: *Profiles of diffusion coefficient and convection velocity fitting the experimental* q_{min} *evolution (i.e. test 5), and associated NBI and total current profiles, for shot #123042 at t=2s.*

References

[1] J.E. Menard et al., PRL 97, 095002 (2006)
[2] Y.R. Lin-Liu and F.L. Hinton, Phys. Plasmas 4 (11) (1997)
[3] J.R. Ferron et al., IAEA (2006)
[4] V. Basiuk et al., Nuclear Fusion **43**, 822 (2003).
[5] Y. Feng et al., Comp. Phys. Comm 88 (1995) 161-172
[6] M. Schneider et al., PPCF **47** 2087-2106 (2005)
[7] M. Murakami et al., Phys. Plasmas 13, 056106 (2006)