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Study of Current Profile Evolution in Presence of Tearing Modes in DIII-D Hybrid Discharges

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Introduction

An intermediate regime for tokamak operation has been obtained in DIII-D [1,2] and in other tokamaks [3] in which the inductive flux consumption is reduced and a broad current profile with the safety factor just above or near the sawtoothing limit is obtained and maintained. The DIII-D tokamak was operated in this regime near the no-wall β limit. High stability and good confinement was achieved at a desired level of $q_{95} \sim 3$ to 4 for durations as long as $35\tau_E$, three times the current-diffusion time. This regime offers the promise of achieving higher fusion gain and yield and/or longer burn duration for ITER.

In these "hybrid" DIII-D discharges, a stationary current profile is only obtained when an m=3/n=2 neoclassical tearing mode (NTM) is present and the minimum safety factor approaches the value of 1. Therefore it is surmised that the required presence of the mode is responsible for maintaining a steady-state current profile. The presence of a single-helicity tearing mode and/or the observed level of alteration in the accompanying temperature (conductivity) profile alone is insufficient to prevent the safety factor from going below unity [2]. A "dynamo" electromotive force (e.m.f.) or current source is hypothesized as a possible explanation [1]. In these "hybrid" discharges, a possible candidate is the modulation of the 3/2 NTM by edge-localized modes (ELM) [2]. Since the stationary current profile is obtained only near q=1, it is also possible that a 1/1-mode may be interacting with the NTM to produce a dynamo effect.

Experiments are under way in DIII-D to study the evolution of current in such discharges and to determine the effect of NTMs and associated phenomena. To aid in this effort, we are carrying out simulations under a variety of plasma conditions to determine the expected current profile evolution using the CORSICA [4,5] code. Using neoclassical conductivity, current evolution is calculated and compared with that experimentally observed. This can be used for estimates of the "dynamo" or the "hyper-resistive" effect.

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This paper presents initial results of such modeling carried out for a DIII-D hybrid discharge. We first show a reference case for code prediction of the current evolution in a conventional discharge and then show the difference between the computed evolution and that observed for a hybrid discharge. In one computation we show that a flattening of the resistivity profile inside the tearing mode island together with a flattening of the core resistivity due to 1/1-modes or other MHD activity can lead to a stationary current profile or at least be a significant contributing factor. These effects may be enhanced by hyper-resistivity [6] resulting in current diffusion. Presently, there is no conclusive evidence that the time-average conductivity profile flattens in the core of a hybrid discharge nor for the presence of small amplitude 1/1 mode structure.

Modeling of Current Evolution with CORSICA

We initialize the code using a desired time slice to obtain an experimental fit to the equilibrium given by EFIT [7]. This is re-converged inside CORSICA to match the EFIT solution (boundary and flux distribution). Using the NCLASS [8] model, we calculate the bootstrap current and resistivity profiles from the corresponding plasma density, impurity and temperature profiles. For the neutral-beam power injected, we calculate the power and particle deposition and the beam-driven current. When time is advanced in these simulations, we can employ either a transport model to evolve profiles or use experimental measurements. The latter method is used in the present calculations since only the evolution of the Ohmic current is of interest and change in the non-inductive current profiles dependent on the kinetic profiles is of incidental interest. (In stationary current profile conditions, the plasma profiles remain constant). The code self-consistently and simultaneously solves the equilibrium using current profiles from Ohm’s law that also provides the loop voltage.

The modeling prediction of the total and Ohmic current profile evolution for a duration of 0.5s from a given DIII-D equilibrium, a non-hybrid-mode discharge 98549, is shown in Fig.1, along with the experimentally observed profiles. Since there were no MHD instabilities in this time interval, predictions based on inductive-resistive evolution

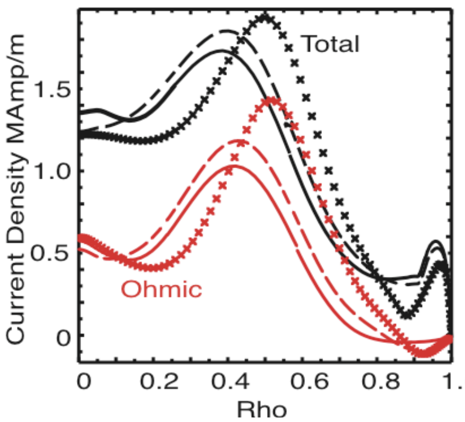

Fig. 1 Comparison of measured and simulated total (black) and Ohmic (red) current profile evolution for a discharge without NTM activity: initial profile (x) and profiles 0.5s later for observed (solid) and computed (dashed) profiles.

should be valid and, as shown, the predicted and measured current profiles are in reasonably good agreement. Uncertainties in equilibrium fits must be small for this comparison and no phenomenon that can interfere with a neoclassical resistive evolution should be present during this simulation interval.

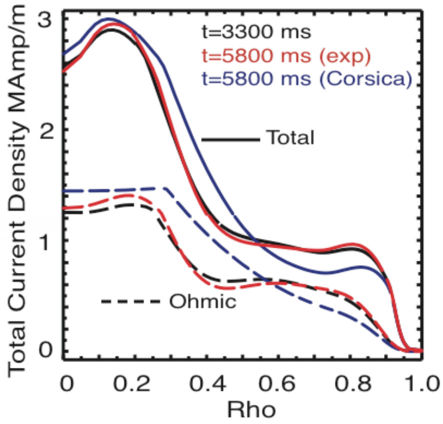

Fig. 2 Simulated and measured total (solid) and Ohmic (dashed) current profiles for DIII-D discharge 117755 conditions with NTM modes present: initial time (black) of 3300ms and those after 2.5s of evolution with observed profiles in red and computed profiles in blue indicating the effect of sawtooth activity on the current profiles.

We have simulated the current profile evolution for a DIII-D hybrid mode discharge, 117755, as computed using the CORSICA code. In this discharge, the safety factor initially falls near 1 but then remains constant late in time near 1 when the 3/2-mode is present, as detected by Mirnov probes. The stationary nature of the current profile is confirmed by Motional Stark Effect data [1,2]. In Fig.2, we show a comparison of the computed and experimentally determined evolution starting at 3300ms into the discharge; this is about 300ms after the onset of a 3/2-mode. In this figure, we show the total and Ohmic current profiles at an initial time of 3300ms and the observed and computed profiles 2.5s later, at 5800ms, where current profile flattening near the axis is readily apparent. In this figure, the result of using a sawtooth model to flatten the conductivity profile inside a q=1 surface is present in the simulated profiles. This takes into account the effect of sawteeth that would be present if the discharge had evolved normally, that is, with sawteeth but without any q~1.5 or NTM dynamo effects. It is evident that the expected sawtoothing evolution is very different from the observed profile as determined from an EFIT reconstruction at 5.8s.

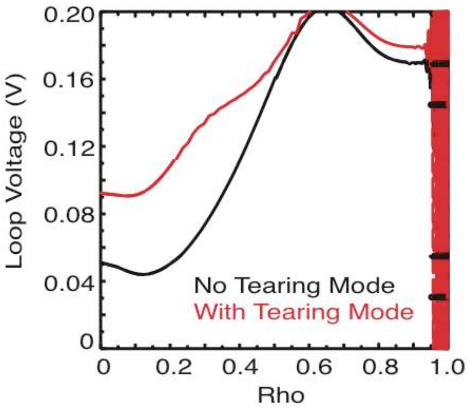

Fig. 3 Comparison of calculated loop voltage profiles using temperature flattening for NTMs (red) and without (black).

The effect of the 3/2-tearing mode on the current evolution was investigated by flattening the electron temperature profile over 9cm at the location of the q=1.5 surface. In Fig.3, we show the computed loop voltage profile with and without the simulated presence of a tearing mode. The difference between these loop-voltage profiles and a flat, steady-state profile would indicate the presence of an effective dynamo voltage profile. In Fig. 4, we compare the simulated current profile evolution (holding the plasma current constant). The initial Ohmic current shown (at t=2700ms) is 300ms before the start of a 3/2-tearing mode. The other curves indicate the Ohmic current profile 3s later with and without the simulation of NTMs and sawtooth-like effects. While the tearing mode affects the current evolution significantly on the outside of the 3/2 surface, the core current density is not significantly affected and, as a result, the minimum q continues to drop well below 1. However, as we showed in Fig. 3 (red), the voltage profile becomes flatter everywhere. We also show in Fig. 4 results of a simulation with a sawtooth model for flattening the resistivity profile inside the q=1 surface along with the flattened temperature profile simulating the NTM effects. We note the significantly smaller change with time in the current profile for the NTM simulation. In this simulation, the current evolution both inside and outside the 3/2-resonant surface is significantly slowed down.

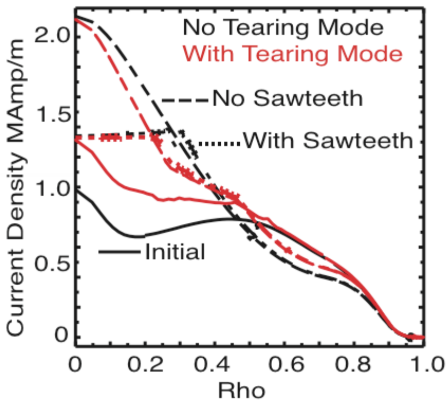

Fig. 4 Comparison of simulated current profile evolution for 3s (to t=5.7s) with (red) and without (black) tearing mode effects where: solid is the initial profile at 2.7s, dashed is the evolved profile including NTM flattening of the temperature profile at q~1.5, and dotted is the evolved profile with both NTM flatting at q~1.5 and inside the q=1 surface.

Summary:

We are using the CORSICA code to model the evolution of hybrid discharges to elucidate qualitative differences between the usual current profile evolution and the observed stationary nature of the current profile in hybrid discharges. By flattening conductivity profiles in both the tearing mode region, q ~ 1.5, and inside the q=1 surface the evolution of the current profile is significantly slowed. With the addition of physics-based hyper-resistivity to model current diffusion, we will explore the possibility of generating stationary current profiles.

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