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Analysis and Modeling of DIII-D Hybrid Discharges and their Extrapolation to ITER

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Introduction. Recent experiments on tokamaks around the world [1-5] have demonstrated discharges with moderately high performance in which the q-profile remains stationary, as measured by the motional Stark effect diagnostic, for periods up to several τ_R. Hybrid discharges are characterize by $q_{\min} \sim 1$, high β_N, and good confinement. These discharges have been termed hybrid because of their intermediate nature between that of an ordinary H-mode and advanced tokamak discharges. They form an attractive scenario for ITER as the normalized fusion performance ($\beta_N H_{89P} / q_{95}^2$) is at or above that for the ITER baseline $Q_{fus} = 10$ scenario, even for q_{95} as high as 4.6.

The startup phase is thought to be crucial to the ultimate evolution of the hybrid discharge. An open question is how hybrid discharges achieve and maintain their stationary state during the initial startup phase. To investigate this aspect of hybrid discharges, we have used the CORSICA code to model the early stages of a discharge. Results clearly indicate that neoclassical current evolution alone is insufficient to account for the time evolution of the q-profile and that an addition of non-inductive current source must be incorporated into the model to reproduce the experimental time history. We include non-inductive neutral beam and bootstrap current sources in the model, and investigate the difference between simulations with these sources and the experimentally inferred q-profile. Further, we have made preliminary estimates of the spatial structure of the current needed to bring the simulation and experiment into agreement. This additional non-inductive source has not been tied to any physical mechanism as yet. We present these results and discuss the implications for hybrid startup on ITER

Modeling Results. A contour plot of EFIT-inferred q versus time and ρ for the startup phase of a typical hybrid discharge is shown in Fig. 1. A plot of the raw MSE data exhibits a similar approach to the steady-state. There are multiple time scales associated with the approach to stationarity. All profiles evolve rapidly during the current ramp, which ends at 1.3 s, and which is close to the beginning of H-mode at 1.265 s. The steady state for the electron temperature is obtained at 1.65 s, while that for the ion temperature, electron density, toroidal rotation, β_N and ℓ_i is obtained close to 2.0 s. The longest time scale is associated with the evolution of the current profile, which does not achieve stationarity until 2.9 s as can be seen in the q = 1.5 contour in Fig. 1. It is natural to divide this portion of the discharge into two parts: the rapidly evolving current ramp (0.3 – 1.3 s) and the more slowly developing current equilibriation stage extending from the end of the current ramp to a point at which the amplitude of a 3/2 tearing mode, already present at 1.1 s, rapidly increases (1.2–2.9 s). These will be considered separately below.

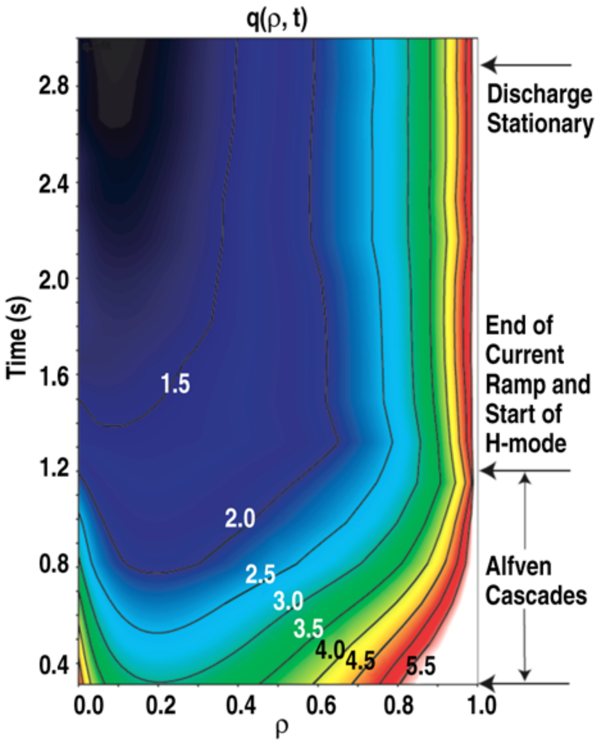

Fig. 1. q as function of ρ and time for a typical hybrid discharge in DIII-D. Contours of integer and half integer values of q are labeled.

We have modeled the startup phase of DIII-D hybrid discharges using the CORSICA code in a manner analogous to that of an earlier study [6]. A neutral beam non-inductive current source based on the NFREYA code, and a bootstrap current source based on the NCLASS model are incorporated into all simulations together with the NCLASS formulation for the conductivity. Experimentally measured kinetic profiles together with the plasma boundary are specified at a discrete set of times and the current profile is then evolved. The resulting current and q-profiles are compared to those obtained from EFIT constrained with MSE data.

Throughout the current ramp, the CORSICA-evolved values of $q_{\min}$ are less than those inferred from EFIT, and the simulation $\rho_{q\min}$ is less than that for EFIT. As the current profile is further evolved, $q_{\min}$ invariably drops below unity, while experimentally, this condition does not prevail as evidenced by the lack of sawteeth in the discharge under consideration. We have also repeated the calculation with a heuristic anomalous fast ion diffusion coefficient, but with the same result. The effect of this was primarily to lower q_0 with the current modification confined to the region $\rho < 0.2$ for the range of diffusion coefficients examined. This is demonstrated in Fig. 2, which shows q-profiles for a sequence of times from EFIT (solid lines) and those from a simulation (dashed lines) in which the current profile was evolved neoclassically including a fast ion diffusion coefficient giving the best fit to the EFIT profiles. Overall, the trends are properly reproduced, but the agreement is less than perfect. These results indicate that some other anomalous current redistribution process is at work, and one that is more global in nature. This may be due to the a fast ion convective effect, fast ion losses, or flux-pumping or dynamo terms not accounted for in the non-inductive source models.

We have also considered the fact that the EFIT profiles may be in error, but there is good experimental support for their overall characteristics. This comes from the observation of reverse shear Alfven modes on the CO_2 interferometer [7]. Figure 3 shows a spectrogram of the CO_2 interferometer signal and the inferred times at which integer and half-integer values of $q_{\min}$ first appear. These times and values are in very good agreement with corresponding EFIT $q_{\min}$ values versus time. In addition, the Alfven modes essentially vanish at ~1.3 s (beginning of H-mode/end of current ramp) where EFIT gives a flat q-profile. The value of $q_{\min}$ from the simulation is lower than the EFIT value at all but the earliest time.

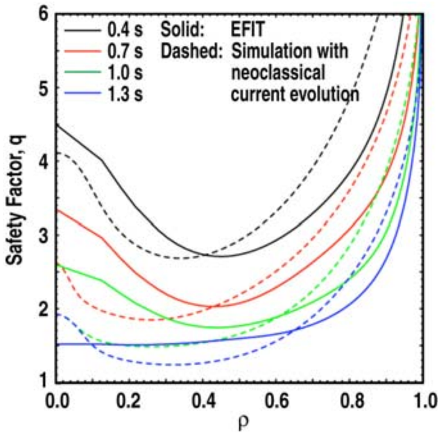

Fig. 2. Comparison q-profiles of simulation with neoclassical current diffusion combined with fast ion diffusion and EFIT.

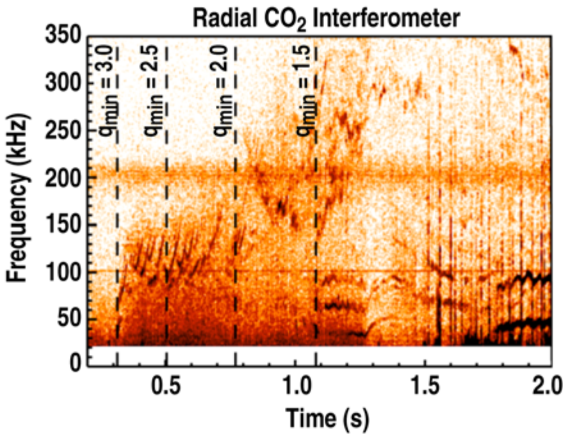

Fig 3. Spectrogram of the CO_2 interferometer signal showing the Alfven cascades and the values of q_{min} inferred from them [7]. Lower frequency tearing modes are also observed beginning at 1.1 s.

We next consider the time interval following the current ramp. This period is characterized by a slow transition to stationarity in which a small amplitude 3/2 tearing mode is present. The simulation was restarted with the profiles at 1.3 s with the result that q_{min} = 1 is encountered at ~3.15 s. This time is little changed if fast ion diffusion is added to the current evolution. Again results suggest that an anomalous process is present. To better understand this we have considered the question of how the current profile must be modified relative to its neoclassically evolved value in order to obtain agreement with the MSE constrained EFITs. We find that an additional non-inductive current is required to obtain maintain $q_{min} > 1$ in the region $\rho < 0.6$. The general shape of the added current is relatively easy to predict, but a great deal of trial and error is required to arrive at a good approximation to the experimental result. The final form of the additive current used is approximately a sinusoid over the range $0 < \rho < 0.6$ and its integral is constrained to be 0 with peak current density < 15% of the peak total current density at 2.0 s. A weak time dependence was included, but it does not have a significant effect on the overall evolution.

With the added non-inductive current, the $q_{min} > 1$ phase can be extended to well past 4.0 s, which was as far as the simulations were carried out. The resulting q-profiles are shown in Fig. 4 together with those from EFIT for several times after the end of the current ramp. Examining the region $\rho < 0.6$ first, it is seen that the simulation is generally greater than the EFIT q. Only at the latest time (4.0 s), when q_{min} drops to 1.0 does the simulation q-value drop below the EFIT value. The general shape of the profiles at the same time are in good agreement but have slightly different values with $\delta q \sim 0.2$. Better agreement can be achieved by refining the form of the additive current density as well as it's time dependence. Without current redistribution of the form considered, diffusive process invariable lead a lowering of q_0 below unity for this discharge.

The difference in the q-profiles region $0.6 < \rho$ is due to the fact that the simulation includes the bootstrap current resulting from the H-mode pedestal, while the EFIT q-profiles do not include an edge current. This feature will be added in the future. The result will be to reduce the q at the edge and increase q further in, bringing the two sets of profiles into closer agreement.

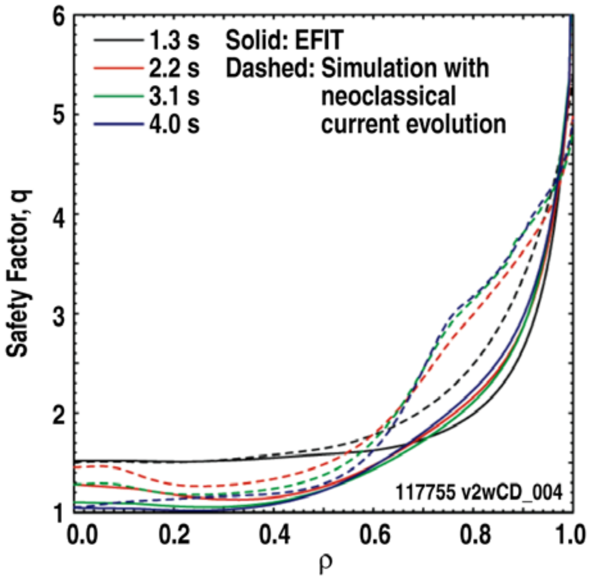

Fig. 4. Comparison of q-profiles from EFIT (solid lines) with those the CORSICA simulation with neoclassical current diffusion (dashed lines). The initial simulation and EFIT profiles differ because the former includes the kinetic pressure.

Implications for ITER. At this preliminary stage of the analysis, it is too early to say precisely what the implications for hybrid modes on ITER will be. However, a few words are in order. In light of the above results, reproducing a startup phase for ITER analogous to those in current experiments will likely be difficult. Tearing modes have been implicated in maintaining the stationary state, but the mechanisms by which this is accomplished are still relatively speculative. Tearing modes are expected to occur in most discharges of interest on ITER, so the possibility exists that some aspects of the physics displayed in present day experiments will carry over to ITER.

The essential question is whether the appropriate initial current profile can be generated and sustained. To this end, numerous current profile control techniques can be applied. Our simulations suggest the magnitude of the required current redistribution is relatively small and its spatial structure is largely confined to the inner half of the plasma where current drive efficiencies are the greatest. Thus these techniques may have to be relied on in order to establish and maintain hybrid-like discharges in ITER.

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