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Current Profile Modeling to Extend the Duration of High Performance Advanced Tokamak Modes in DIII–D*

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Introduction

In DIII–D, as in a number of tokamaks, high performance is obtained with various optimized magnetic shear configurations that exhibit internal transport barriers. Negative central shear (NCS) discharges [1] are created transiently during the current ramp-up by auxiliary heating and current drive from neutral beam injection. Both q_{min} and the radius at which it occurs, ρ_{qmin}, decrease with time as the Ohmic current diffuses inward. The *q*-profiles calculated using EFIT [2] with external magnetic and Motional Stark Effect (MSE; to determine the magnetic field pitch angle) measurements as constraints are comparable to those calculated with the Corsica code [3], a time-dependent, 2D equilibrium and 1D transport modeling code. Corsica is used to predict the temporal evolution of the current density from a combination of measured profiles (e.g. n_i and Z_{eff}), transport models and neoclassical resistivity. Using these predictive capabilities, we are exploring methods for increasing the duration and ρ_{qmin} of the NCS configuration by local control of the current density profile with simulations of the possible control available from the electron cyclotron heating and current drive system currently being upgraded on DIII–D.

Corsica is a comprehensive simulation package that provides a flexible environment for modeling toroidal plasmas. It includes a robust 2D equilibrium solver (free and fixed boundary) plus 1D (toroidal flux) core transport which are simultaneously iterated during time-dependent modeling of plasma evolution. A scripting language provides a flexible user interface to implement models for heating, current drive and transport. All simulation variables are available to the user along with access to a database of the DIII–D parameters. Corsica is currently used for simulation of DIII–D experiments and for design applications for ITER and for alternate toroidal systems. Equilibria determined from EFIT using measurements and those calculated by Corsica have compared favorably [4] for previous simulations of resistive current diffusion using measured density, temperature and Z_{eff} profiles for L–mode edge NCS and high β_p discharges.

We use a model for NCS heat transport which has a parametric dependence on the plasma conditions with a transport barrier dependence on the minimum of the safety factor profile, *q*, qualitatively consistant with experimental observations. The electron heat conductivity is given by $\chi_e = c * (T_e^{3/2}/B^2T_i) * f(s) * q^2$ where $f(s) = 1/[1+(9/4)*(s-2/3)^2]$ is a fit to χ/χ_{Bohm} from fluctuation simulations by Waltz [5] and $s=r\nabla q/q$ is the shear parameter. This representation provides a weak barrier to the electron thermal conduction. A strong ion barrier is simulated by the ion thermal conductivity model $\chi_i = c1*\chi_{neo}+c2*\chi_e*H(\nabla q)$ which

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is ion neoclassical (χ_{neo}) inside the $\rho_{q\min}$ and proportional to χ_e outside the barrier with H(∇ q) the Heaviside function.

Our intention is not to do a detailed investigation of transport models but rather to provide a reasonable model of heat conductivity to be able to simulate effects of electron cyclotron heating (ECH) and current drive (ECCD) on confinement in NCS configurations. We adjust free parameters (c, c1 and c2) in the model to obtain a reasonable representation of the temporal evolution of electron and ion temperature profiles consistent with those measured in selected DIII–D shots. In all cases, we use the measured density profiles rather than self-consistently solve for particle sources and particle transport at this time.

In these results, we employ a simple model for the ECH power deposition by providing an externally supplied heat source for the electrons. The heating deposition location and profile are specified as a function of the toroidal flux coordinate to allow us to independently vary the heating dynamics. For the results shown here, we assume a Gaussian profile, typically using a width of $\delta\rho$=0.05 (δr~3 cm in minor radius), with ρ defined as the square root of toroidal flux. All powers are interpreted as that absorbed by the plasma. Similarly, the current drive location and profile are specified with the total current (integrated over the assumed profile) modeled as $I_{ECCD}=\Gamma P_{ECH}/n_e R$ with $\Gamma=0.005T_e$ providing current drive efficiency consistent with earlier experiments [6] with a dependence on T_e but fixed Z_{eff} and trapped particle effects in these simulations. Future work will integrate the existing TORCH [7] code into this ECH modeling effort.

Transport Model Results

Although different discharges have been simulated, we concentrate here on the DIII–D shot 92668 representative of an experimental series of high performance NCS discharges with L-mode edges. Typically, these shots rise to high neutron reactivity but eventually disrupt without additional control due to very peaked pressure profiles. We initialize the simulations for shot 92668 at 1.45 s with full current I_p=1.5 MA, high temperature, T_e=6 keV and T_i=19 keV, and electron density of 0.7×10^{20} m^{-3}. For the results presented here, Corsica is run with fixed, measured density and Z_{eff} profiles and a fixed-boundary equilibrium initialized to the shape determined from the MSE-constrained EFIT calculation. In Fig. 1(a) we show a comparison of the experimental *q*-profile and the initial Corsica equilibrium.

In Fig. 1(b) we show the temperature profiles obtained from the transport model (no ECH or ECCD) and note that, by adjusting the free parameters, the model produces profiles that are reasonably consistent with those measured in the experiments. We ran simulations for the purpose of investigating the combined effects of electron cyclotron heating and current drive to help sustain the NCS mode for times long with respect to the energy confinement time of τ_E~0.08 s for this shot. In Fig. 2(a), we show the temperature and heat conductivity profiles after 0.5 s of evolution to 1.95 s using 5 MW of ECH heating power applied at ρ=0.5. As is readily apparent in the conductivity and temperature profiles, the weak electron and strong ion transport barriers at $\rho_{q\min}$ ~0.55 are maintained until this time; temporal variations are discussed in the following section. In Fig. 2(b) we plot the current densities and *q* profile at this time where the steep rise in bootstrap current at the barrier and the ECCD component, a total of 185 kA, are shown. Using 5 MW of ECH at ρ=0.5, just inside $\rho_{q\min}$, we have been able to maintain the location of $\rho_{q\min}$ and the high performance phase for the duration of heating of over approximately seven energy confinement times. As discussed in following section, 5 MW of heating has had a significant effect on maintaining the NCS configuration.

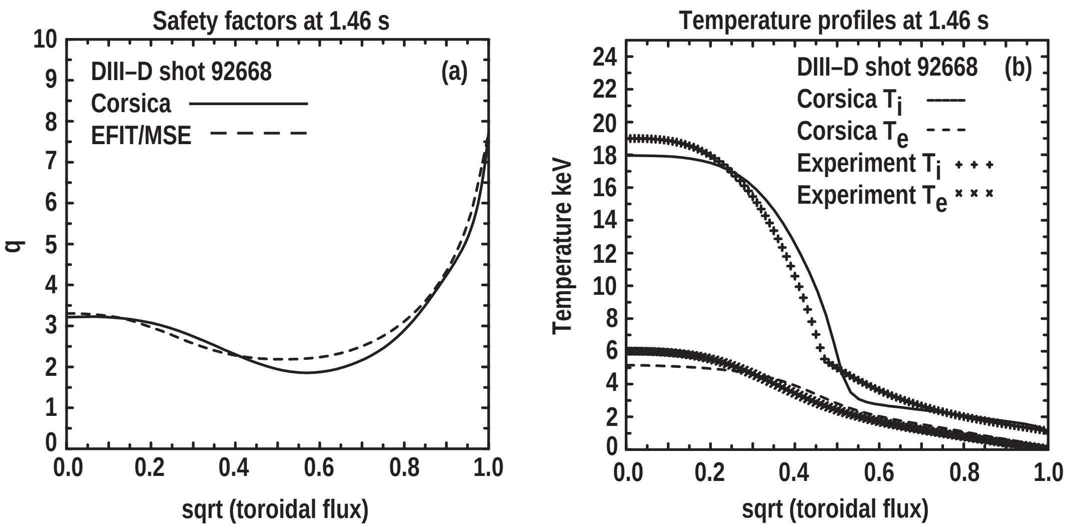

Fig. 1. Corsica initialization to experimental measurements at 1.46 s.

Heating and Current Drive Simulation

Several simulations were run from the initialization time at 1.45 s until $q_{\min}$ dropped below 1 for the 5 MW reference case which occurred at 3.5 s. Four ECH power settings were used; 0 MW, 1 MW, 5 MW and 10 MW. In Fig. 3, we plot the time variation of q_0 and $q_{\min}$ at the different applied power levels with variations in ρ_{qmin} and the poloidal beta (performance measure) shown in Fig. 4. The break in the curves occur at the point where Ohmic diffusion moves the minimum of q inside the heating location at ρ=0.5. Once $\rho_{q\min}$ moves inside the heating location, it begins to move inward at a (faster) rate consistent with the resistive diffusion of Ohmic current and the heating becomes less effective for the transport model in use.

In these simulations, we observe that at the 1 MW level we are minimally able to modifythe tendency for $\rho_{q\min}$ to move inward as the Ohmic current diffuses in from the edge. At the 5 MW heating level we can maintain a large $\rho_{q\min}$ for several energy confinement times, duration ~ 12 τ_E until the Ohmic diffusion finally pushes it past the heating location.

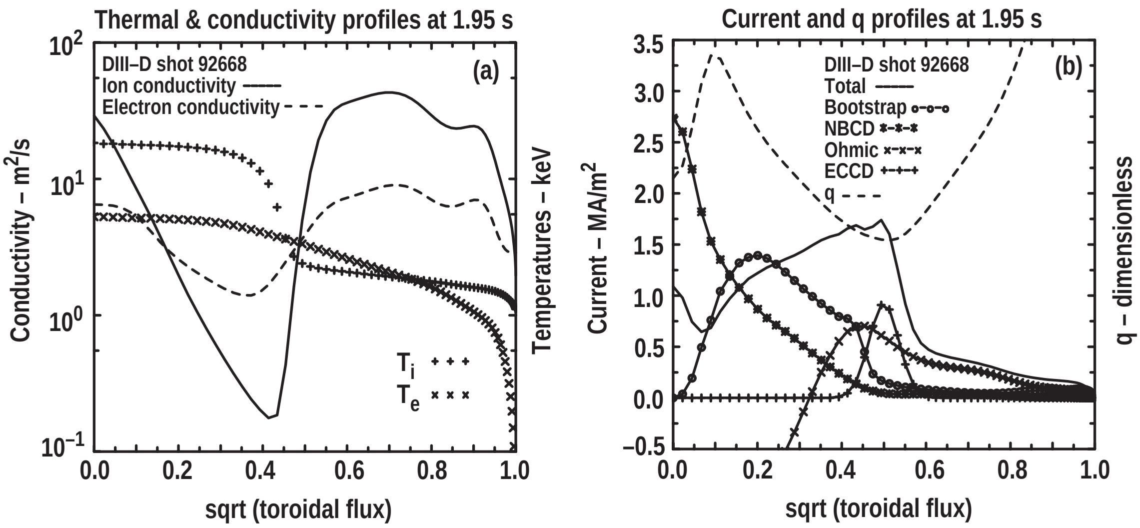

Fig. 2. Profiles of electron and ion heat conductivities and temperatures and the current densities and q-profile after 0.5 s of evolution to 1.95 s.

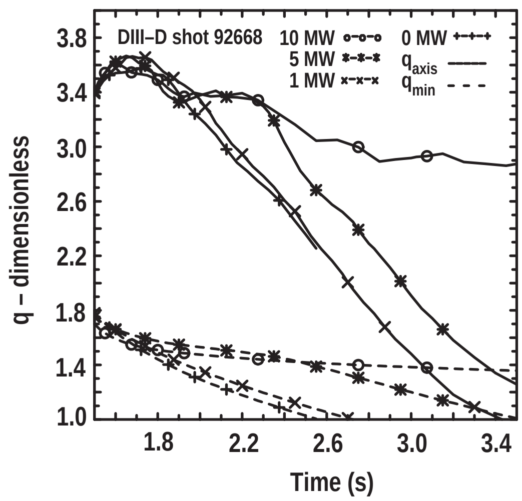

Fig. 3. Temporal evolution of q_0 and q_{min} for the four power levels simulated.

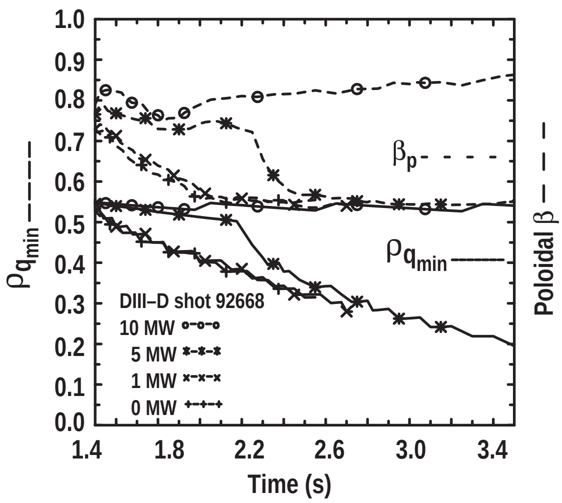

Fig. 4. Temporal evolution of ρ_{qmin}, the position of q_{min}, and poloidal beta for the four power levels simulated

At the 10 MW power level, we were able to maintain the NCS configuration for the entire simulation interval. We are maintaining the barrier by a combination of direct current drive due to ECH plus an enhanced bootstrap current due to the electron heating and its modification of the transport barrier. The total direct current drive from the ECH power is ~30 kA at 1 MW, ~200 kA at 5 MW and ~400 kA at 10 MW with the current drive model used and the parameter variations resulting from the additional electron heating.

These results are critically dependent on the transport model in use. We adopted a philosophy of spatially smoothing the conductivity both as a means of simulating the experimentally reasonable temperature profile shapes and to make code convergence more robust. This limits the steepness of the barrier region obtained. By removing this constraint, we would achieve stronger pressure gradients in the barrier region, albeit inconsistent with any observed in DIII–D to date, which would further enhance the bootstrap current drive at the barrier. Finally, effects due to changes in the density profile were not included in these results. Any steepening of the density profile would enhance the bootstrap current locally to the barrier region and further enhance our ability to maintain the minimum in q and thus, the barrier itself. Future work will be aimed at improving the transport model and incorporating other models. We will include models of particle transport to determine their effect on maintaining the barrier. At present, we have the encouraging predication that the upgraded ECH systems will have a significant effect on our ability to control the transport barrier dynamics in DIII–D experiments.

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