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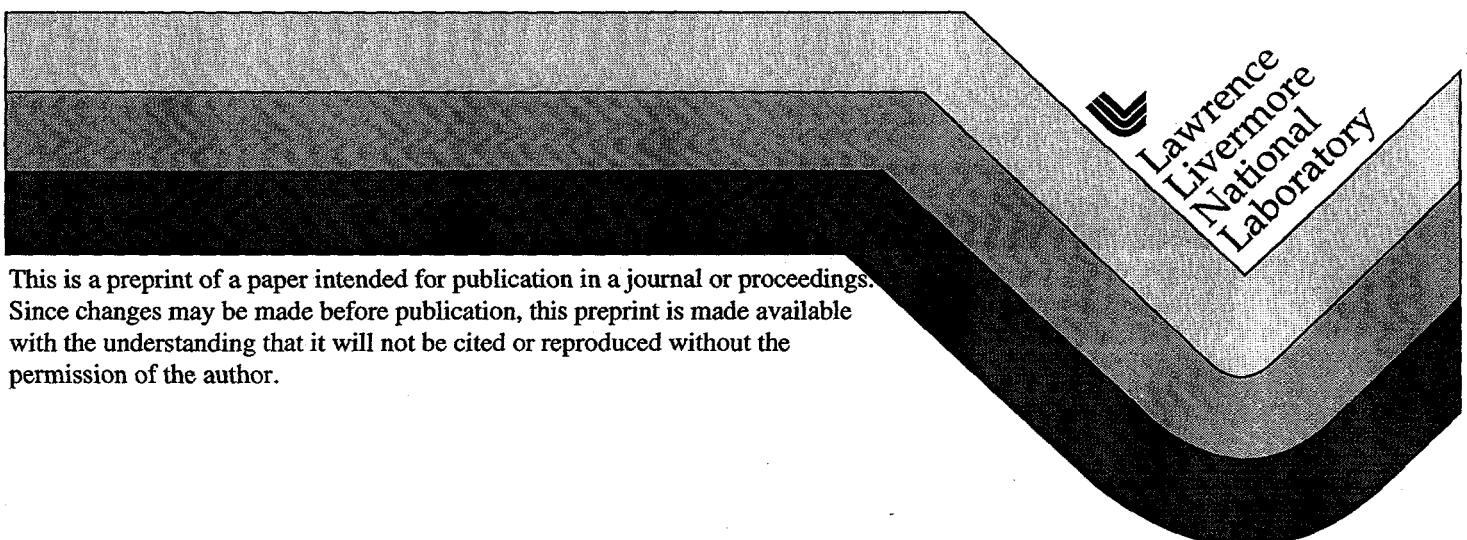
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Modeling of current profile evolution and equilibria in negative central shear discharges in the DIII-D experiment.*

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1.0 Abstract

Recent DIII-D advanced tokamak experiments with negative central shear (NCS) have resulted in operation at high normalized β , $\beta_N = \beta / (I/aB)$, to 4.2, confinement enhancement factors to $H=4$ ($H = \tau_E / \tau_{ITER-89P}$), and record neutron rates for DIII-D to 2.4×10^{16} neutrons/sec. These data were obtained during high triangularity, single and double null diverted operation with peaked (L-mode) and broad (H-mode) pressure profiles. We are modeling the spatial and temporal current profile evolution for these discharges using Corsica, a predictive 1-1/2 D equilibrium and transport code. Current profile evolution is self-consistently determined by including current diffusion resulting from current drive due to early neutral beam injection during the ohmic current ramp-up phase of the discharge and the bootstrap current drive associated with pressure profile evolution.

1.0 Introduction

The prospect for achieving high performance discharges in reduced size advanced tokamaks has stimulated much of the current interest in negative central shear (NCS) experiments. Recent studies^{1,2} have indicated that NCS is a leading candidate scenario for operation in steady state due to improved stability to high-n ballooning modes and bootstrap current density aligned with the total current profile and it has been proposed as an advanced confinement scenario in ITER³. We are applying Corsica to model DIII-D discharges to explore techniques to improve and sustain these discharges, ultimately leading to steady-state.

Corsica⁴ is a comprehensive, predictive toroidal plasma simulation code being developed for design and simulation of existing experiments and of future experiments such as ITER or other advanced tokamaks and alternatives. Corsica is currently running with the combined capabilities of 1D tokamak transport codes and 2D free-boundary equilibrium and edge modeling codes. It is being

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used to model ITER ohmic operation and to assess feedback control capabilities and power requirements. Previous DIII-D L-mode simulations have compared favorably with the EFIT analysis code for high β_p operation and for the low pressure phase of NCS discharges. We are now extending this modeling to high performance phases of NCS and weak shear discharges in DIII-D.

2.0 Simulation methodology

We are presently simulating the temporal evolution of the current profiles to develop an understanding and validation of the models for forming and sustaining the high performance NCS configuration. At this time, we use experimental measurements of the density and temperature profiles rather than model the particle and energy transport. We take as input the measured electron and impurity densities and the electron and ion temperatures and infer the ion density and effective charge (Z_{eff}) from quasi-neutrality using carbon as the main impurity. We initialize the equilibrium by choosing the pressure (p') and current (ff') parameterizations used in fitting data with EFIT. A free boundary calculation provides a starting equilibrium with forced convergence to the plasma current and fitted values of the poloidal field coil currents to account for currents in structures. This prescription allows us to directly compare with the EFIT results and boundary shapes produced in this manner are in generally good agreement. The simulated discharge is evolved from this initial state using a fixed boundary equilibrium calculation while simultaneously accounting for current diffusion.

In previous simulations, an approximate particle orbit model resulted in too little neutral beam current drive on axis. We have replaced this portion of our neutral beam injection code with an orbit following calculation for the Monte Carlo simulation of neutral beam current drive. The injection process is now tightly coupled to the local equilibrium flux surfaces with current drive determined from the residence time of particles in flux zones. By evaluating the trapped, passing, and lost particle distributions we infer the direct current drive from passing beam particle orbits and the bootstrap contribution due to the trapped injected ions.

3.0 Simulation Results

We have begun our modeling with two different high performance discharges. Shot 84682 is a double null, negative central shear discharge with peaked pressure profiles⁵. Confinement factors up to $H \sim 2.5$ were obtained while maintaining the pressure profile with an L-mode edge which allows for good penetration of the neutral beams. The inverted q -profile is achieved by early neutral beam injection during the ohmic current ramp-up phase of the experiment. Ion temperatures in excess of 15 KeV were obtained with peaked density profiles, $n(0)/\langle n \rangle \sim 2.2$. A second case, shot 88964, is a single null, weak central shear discharge with H-mode-like pressure profiles giving a broader deposition profile for the neutral beam injection. The weak shear is formed at reduced neutral beam injection power during the ohmic ramp. This DIII-D shape is representative of the JET and ITER advanced tokamak scenarios.

In Figure 1, we show the plasma current and neutral beam injection histories for these two shots along with the simulation time interval. We model the neutral beam injection as two aggregate sources having the proper geometry for the two beamline orientations on DIII-D and step the average power in time consistent with the experimental variations. Corsica is run in time dependent

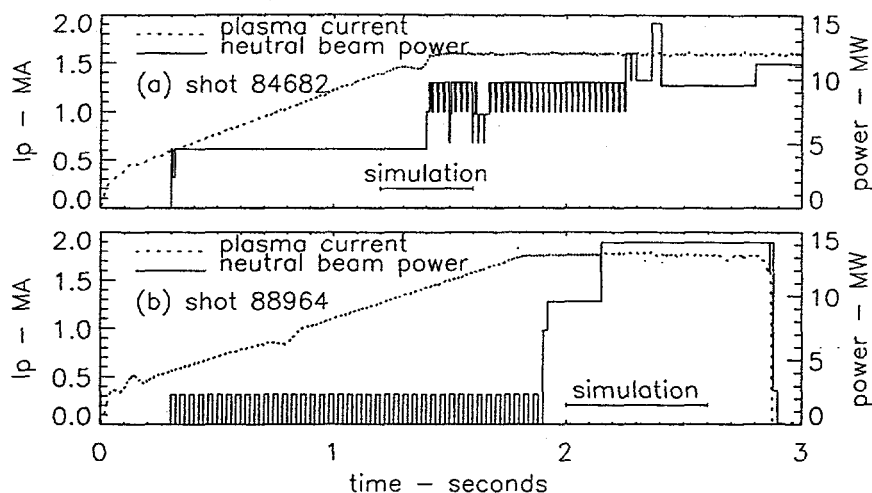


Figure 1. Time history of plasma current and neutral beam power injected.

mode to simulate the evolution of the equilibrium associated with the current diffusion process and obtain spatial-temporal profiles of plasma parameters. We show profiles of the total, ohmic, bootstrap, neutral beam driven current densities in Figure 2 at times near the peak stored energy. As indicated in Figure 3a for the NCS simulation (84682), we obtain good agreement between the simulated q -profile evolution and EFIT analysis outside of $\rho=0.2$ ($\rho = \sqrt{[\text{normalized toroidal flux}]}$), where we note good agreement with the minimum value of q and of q_{95} . Inside $\rho=0.2$, the current drive due to neutral

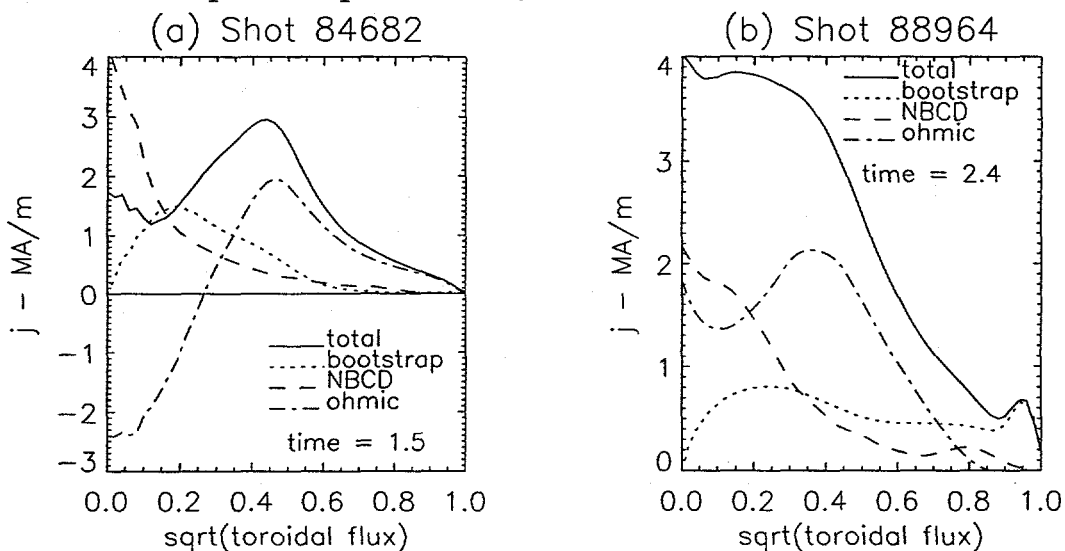


Figure 2. Current density profiles at times near peak stored energy

beam injection dominates the total current and forces the simulation q_0 to drop below that inferred from the EFIT reconstruction. For the weak shear simulation case, Figure 3b, there is agreement over most of the profile during the entire simulation as indicated at times $t=2.0$ and 2.6 s. However, the predicted q -profile evolution does not show the weak bump near $\rho \sim 0.35$ that arises in the EFIT analysis during the times when the density and temperature and, presumably, the ensuing current distribution are rapidly changing. The presence of this bump is critically dependent on fit parameters used in the analysis and on reconstruction constraints such as the motional Stark effect measurement of the local magnetic field. We are investigating the details of the current drive associated with the neutral beam injection which dominates these and all high performance discharges in DIII-D.

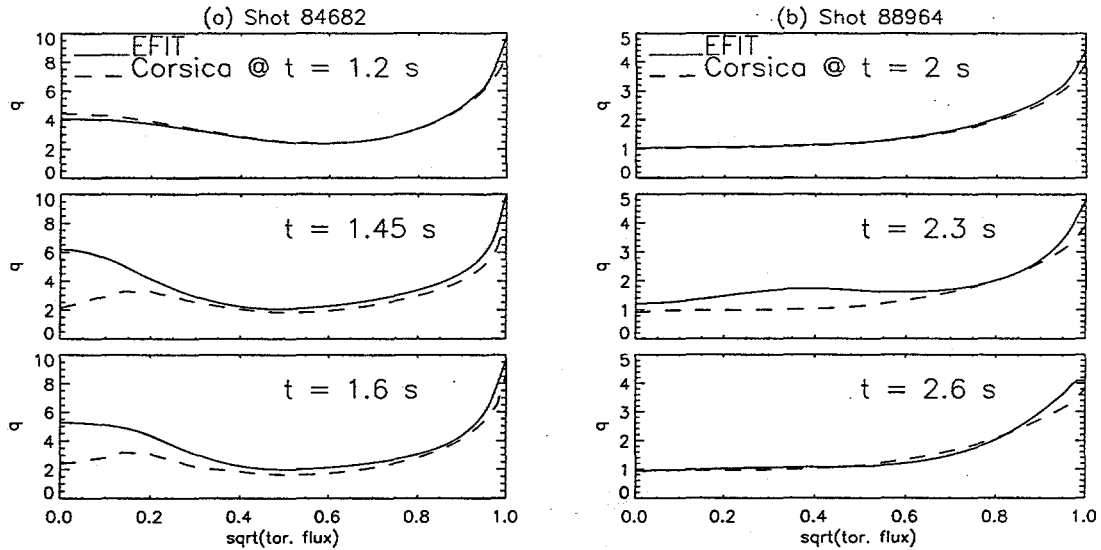


Figure 3. Simulation q -profiles with data fits from EFIT for comparison.

In summary, the initial results at simulating the formation of high performance discharges in DIII-D using our new neutral beam current drive calculation in a fully predictive simulation code are encouraging. We are able to simulate the characteristics of the current profile formation during the evolution of these complex, high performance discharges and we are in general agreement with the experimental data fitting. Discrepancies due to the peaking of the neutral beam current drive near the magnetic axis are a concern and we are investigating the details of these differences. In future simulations, we will be incorporating the use transport models.

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