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Progress toward fully noninductive, high beta conditions in DIII-D^{a)}

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The DIII-D Advanced Tokamak (AT) program in the DIII-D tokamak [J. L. Luxon, *Plasma Physics and Controlled Fusion Research*, 1986, Vol. I (International Atomic Energy Agency, Vienna, 1987), p. 159] is aimed at developing a scientific basis for steady-state, high-performance operation in future devices. This requires simultaneously achieving 100% noninductive operation with high self-driven bootstrap current fraction and toroidal beta. Recent progress in this area includes demonstration of 100% noninductive conditions with toroidal beta, $\beta_T=3.6\%$, normalized beta, $\beta_N=3.5$, and confinement factor, $H_{89}=2.4$ with the plasma current driven completely by bootstrap, neutral beam current drive, and electron cyclotron current drive (ECCD). The equilibrium reconstructions indicate that the noninductive current profile is well aligned, with little inductively driven current remaining anywhere in the plasma. The current balance calculation improved with beam ion redistribution that was supported by recent fast ion diagnostic measurements. The duration of this state is limited by pressure profile evolution, leading to magnetohydrodynamic (MHD) instabilities after about 1 s or half of a current relaxation time (τ_{CR}). Stationary conditions are maintained in similar discharges ($\sim 90\%$ noninductive), limited only by the 2 s duration ($1\tau_{CR}$) of the present ECCD systems. By discussing parametric scans in a global parameter and profile databases, the need for low density and high beta are identified to achieve full noninductive operation and good current drive alignment. These experiments achieve the necessary fusion performance and bootstrap fraction to extrapolate to the fusion gain, $Q=5$ steady-state scenario in the International Thermonuclear Experimental Reactor (ITER) [R. Aymar *et al.*, *Fusion Energy Conference on Controlled Fusion and Plasma Physics*, Sorrento, Italy (International Atomic Energy Agency, Vienna, 1987), paper IAEA-CN-77/OV-1]. The modeling tools that have been successfully employed to both plan and interpret the experiment are used to plan future DIII-D experiments with higher power and longer pulse ECCD and fast wave and co- and counterneutral beam injection in a pumped double-null configuration. The models predict our ability to control the current and pressure profiles to reach full noninductivity with increased beta, bootstrap fraction, and duration. The same modeling tools are applied to ITER, predicting favorable prospects for the success of the ITER steady-state scenario. © 2006 American Institute of Physics. [DOI: 10.1063/1.2173627]

I. INTRODUCTION

The goal of the Advanced Tokamak (AT) program on DIII-D¹⁻³ is to develop the scientific basis for steady-state, high-performance operation in future reactors. For steady-

state operation, all of the plasma current must be supplied by noninductive (NI) means, namely, means other than the typical inductively driven current where the plasma current is the secondary of a transformer. A high fraction of bootstrap current, the self-generated current due to plasma density and temperature gradients⁴, $f_{BS}=I_{BS}/I_p \propto \beta_N$, is desirable to minimize the recirculating power where the normalized beta, $\beta_N=\beta_T(\%)/[I_p(\text{MA})/a(\text{m})B_T(\text{T})]$. Here β_T is the ratio of the

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plasma pressure to the magnetic pressure, I_p is the plasma current, a is the plasma minor radius, B_T is the toroidal magnetic field, and q is the safety factor. The remainder of the plasma current is provided by external, noninductive means. High-performance operation is needed to maintain sufficient fusion gain with reduced engineering parameters. High fusion gain ($\propto \beta_T \tau_E$) requires high values of normalized β_N and high confinement, H_{89} , at a modest safety factor, q_{95} , where H_{89} is the ratio of energy confinement time (τ_E) relative to International Thermonuclear Experimental Reactor (ITER) L-mode scaling.⁵ Combining these parameters, the operation requires high normalized fusion performance, $G = \beta_N H_{89} / q_{95}^2$.

Toward these goals, AT experiments on DIII-D uniquely strive to integrate the key elements that are required for sustained AT operation:^{6,7} high β operation at modest q , high confinement, and efficient current drive. These experiments take advantage of recent improvements on DIII-D, including resistive wall mode (RWM) stabilization via plasma rotation and active feedback control with external, and more recently additional internal nonaxisymmetric coils,⁸ which allows routine operation above the no-wall beta limit.⁹ In these experiments, off-axis electron cyclotron current drive (ECCD) has been shown to be effective for modifying and/or controlling the current profile in high β plasmas.^{6,7} Density control of AT discharges⁷ with edge localized modes (ELMs) using divertor cryopumps facilitates high current drive efficiency at reactor relevant collisionality. An advanced plasma control system allows integrated control of these elements. Neoclassical tearing modes (NTMs) are avoided through current profile control, although active feedback stabilization using localized ECCD^{10–13} has also been demonstrated.

Recent progress in this area includes demonstration of fully noninductive conditions using off-axis ECCD. Equilibrium reconstructions indicate that the noninductive current profile is well aligned, with little inductively driven current remaining anywhere in the plasma. These conditions were obtained at high beta: $\beta_T = 3.5\%$ and $H_{89} = 2.4$ at $q_{95} = 5.0$, achieving $G = 0.3$. Therefore these plasmas have demonstrated “in-principle” steady-state conditions with the fusion performance required for ITER steady-state operation.

In these studies, modeling played a key role in interpreting experimental data and guiding the experiments. In particular, understanding the detailed current profile evolution is crucial to extending high-performance plasmas to steady state. Understanding the current profile evolution is very challenging because of the complex interactions amongst the bootstrap current, external current drive, transport and magnetohydrodynamic (MHD) stability. This requires integrated modeling tools, and these tools need to be validated against experiments. Using both empirical and theory-based models, AT experiments are both planned and interpreted in light of these simulations. By doing so, predictive modeling is validated against the experiment. This modeling projects longer sustainment of 100% noninductive current drive in DIII-D at higher fusion performance with hardware improvements now becoming available. The same modeling has also been applied to ITER steady-state scenario development with favorable results.

In this paper, we discuss progress toward fully noninductive, high beta conditions in DIII-D. In Sec. II, we discuss the characteristic of these discharges: noninductive current balance through measurements, analysis and simulations. Pressure profile evolution to MHD instability and achievement of stationarity consistent with the present hardware limitations are discussed. In Sec. III, optimization for fully noninductive, high beta conditions is discussed by considering choice of operational parameters, choice of plasma density and current drive (CD) alignment. In Sec. IV, we discuss transport modeling using a theory-based, gyro-Landau fluid (GLF-23)¹⁴ model. We show validation of this model against plasma profiles of a single discharge as well as trends with parametric variations, in particular, a density scan. We then apply the model to predict DIII-D operation with upgraded capabilities and an ITER steady-state scenario.

II. CHARACTERISTICS OF 100% NONINDUCTIVE, HIGH β DISCHARGES

Fully noninductive conditions at increased beta have been obtained by careful modeling and extension of the discharge obtained in 2002⁷ with $q_{\min} > 1.5$, $\beta_N = 3.1$, $f_{BS} \sim 60\%$. Predictive modeling¹⁵ using both scaled-experimental¹⁶ and theory-based GLF23¹⁴ transport models indicated that increasing the neutral beam power would result in plasmas reaching a noninductive current fraction $f_{NI} \approx 100\%$ at higher β . Experiments in 2003 were carried out to test these predictions.³ Using 2.5 MW of off-axis (normalized minor radius, $\rho = 0.4 - 0.5$) ECCD and up to 15 MW neutral beam injection (NBI) with $q_{95} = 5.0$, nearly 100% of the plasma current was sustained for ~ 0.7 s at high beta ($\beta \approx 3.6\%$, $\beta_N \approx 3.5$). The loop voltage was reduced to near zero and the net noninductive fraction of 100% was achieved. However, internal loop voltage (VLOOP) analysis¹⁷ indicated that local inductive current was not zero near the plasma center. The negative inductive current there is a reaction to excessive NBCD near the axis which led to neutral beam overdrive near the axis and an increase in the central current density. This resulted in a decrease in the central safety factor q_0 , causing a 3/2 NTM, which terminated the high-performance phase. These discharges had somewhat deteriorated confinement ($H_{89} \approx 1.9$ rather than 2.3–2.4) and reduced rotation velocity relative to the original discharges in 2002.

Several more recent improvements led to confinement improvement. Figure 1 shows the time histories of plasma parameters in such a discharge. Beta feedback [The plasma control system adjusts NB power in an attempt to keep the β (stored energy) value in agreement with a prescribed β waveform.] was initiated shortly after the L-H transition [spontaneous transition from L-mode to H-mode (high confinement)] at $t = 0.4$ s, resulting in significant improvement in the reproducibility of the q profile prior to the high-performance phase, providing more control over $q_{\min}$ and $q_0 - q_{\min}$, where $q_{\min}$ is the minimum safety factor and $q_0 - q_{\min}$ represents the magnetic shear in the core. Also, feedback control of the nonaxisymmetric magnetic field was improved. The higher rotation associated with the reduced error

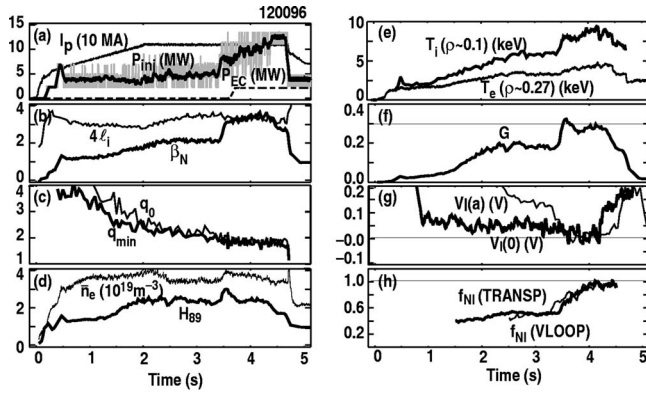


FIG. 1. Time histories of parameters for a discharge that is locally and globally fully noninductive: (a) plasma current, NBI and ECCD power; (b) normalized beta and four times internal inductance (approximate no-wall beta limit); (c) central and minimum safety factor; (d) line-average electron density and confinement enhancement factor; (e) ion and electron temperature near the axis; (f) normalized fusion performance, $G = \beta_N H_{89} / q_{95}^2$; (g) surface and axial loop voltage; and (h) noninductive current fractions from the internal loop voltage and transport analysis.

field led to improved confinement and lower NBI power demand in the high-performance phase, and thus to less current drive near the axis. Good confinement, $H_{89}=2.4$, was restored, and fusion performance $G=0.3$ was achieved in this discharge. Both the axial and surface voltage are nearly zero (<10 mV), and both loop voltage analysis and evaluation by a transport code show that 100% noninductive current with good CD alignment is achieved.

In order to show that 100% noninductive conditions are obtained globally and locally across the plasmas, we will

discuss three methods used to obtain the inductive current density profile: internal loop voltage analysis, transport analysis, and poloidal field evolution modeling. The VLOOP analysis discussed earlier is derived primarily from experimental data and is shown in Fig. 2(a). The inductive current is the product of the neoclassical conductivity and parallel electric field.¹⁷ The latter is calculated from the time derivative of the poloidal flux based on a series of equilibrium reconstructions using the equilibrium fitting code, EFIT,¹⁸ and is rather insensitive to the parameterization used in EFIT. The total current density profile is sensitive to this parameterization since it is calculated from the spatial derivatives of the poloidal flux. The next method of analyses is carried out by a transport code [TRANSP¹⁹] calculation based on a series of “kinetic” equilibrium reconstructions that are consistent with measured profiles and the equilibrium reconstruction discussed above. The components of the noninductive current are calculated from various current source models as shown in Fig. 2(b). The bootstrap current is estimated to be 59% with the Sauter model²⁰ and NCLASS model.²¹ These models are somewhat sensitive to the input profiles near the axis and edge. The neutral beam current drive fraction is calculated to be 31% from the TRANSP Monte-Carlo beam slowing down calculation, and ECCD calculated by TORAY-GA code²² is 8%. The difficult part of this analysis is to obtain a reliable estimate of inductive current, the remaining part of the total current. Despite a quest for high-quality kinetic equilibrium reconstruction, the total current derived from the kinetic equilibrium reconstructions lacks spatial resolution, and thus the inductive current derived from it is similarly limited in accuracy. The third

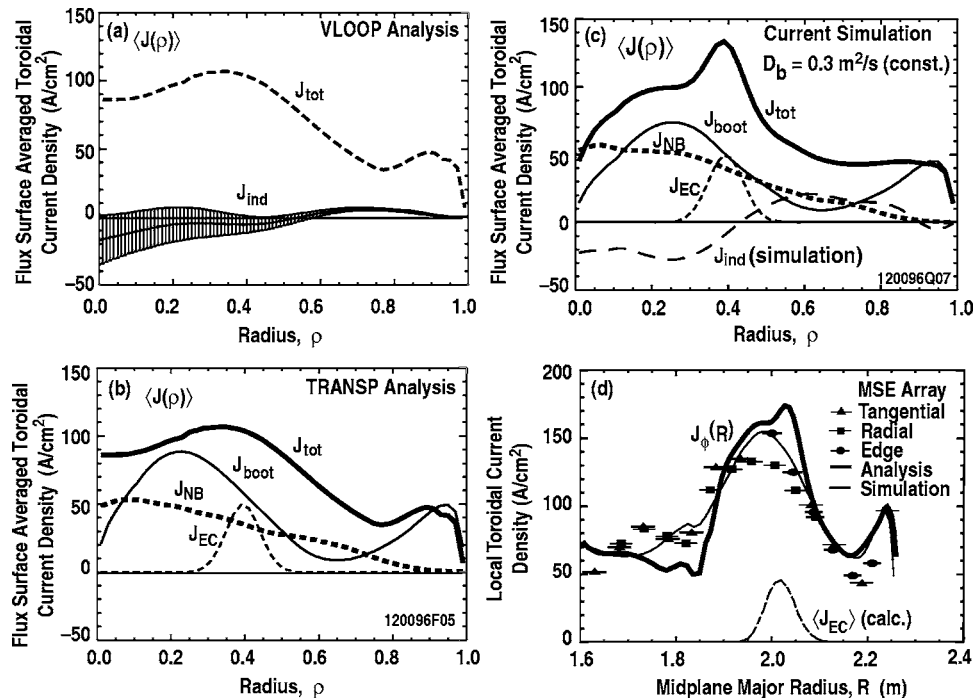


FIG. 2. Three methods of analyses for the current balance: (a) inductive and total current profile from the internal loop voltage analysis based on a series of equilibrium reconstructions; (b) total current, bootstrap, neutral beam, and EC current drive profile based on transport analysis; and (c) profiles of total, bootstrap, NBI, and EC current drive based on the current evolution simulation using TRANSP code; and (d) toroidal current density profiles as functions of the major radius derived from the MSE measurement, the transport analysis and the current evolution simulation.

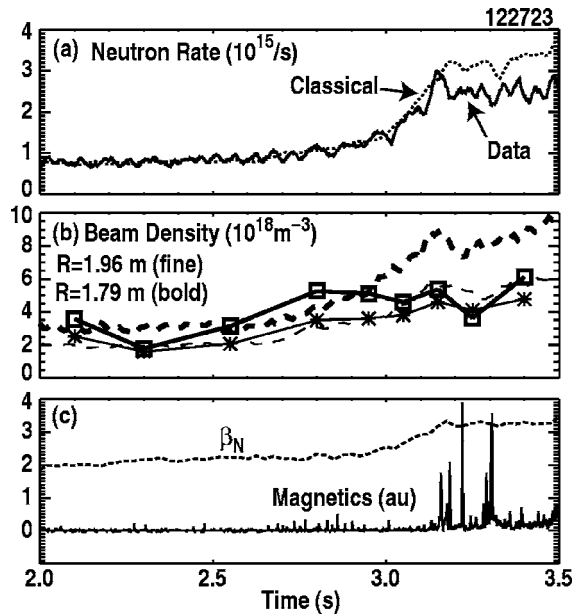


FIG. 3. Observations of neutral beam ion behavior: Time histories of: (a) neutron rate (solid line) and classical slowing down prediction (dashed); (b) beam ion densities at two vertical chords near axis (square) and at larger radius (star) measured by the new fast ion diagnostic and their prediction by TRANSP classical slowing-down calculations; (c) magnetic perturbation and normalized beta.

method, simulation of the poloidal field evolution using a transport code based on the measured time-dependent kinetic profiles, allows us to calculate the total current (and thus the inductive current) with better spatial resolution. The resultant inductive current is shown in Fig. 2(c). The inductive current inferred from the simulation has more structure than that from the VLOOP analysis [Fig. 2(c)]. We consider two possibilities why this might occur: NBCD and bootstrap current models.

Recent fast ion diagnostic data verify that beam ions are redistributed in the core during these discharges. The diagnostic uses spatially resolved charge exchange recombination (CER) spectroscopy of Doppler-shifted D_α light from beam ions in the energy band between 40 and 80 keV (beam injection energy).²³ Figure 3 shows time histories of measured beam ion densities along two different vertical chords²⁴ together with neutron rate and MHD activity for a more recent, but similar $f_{NI} \approx 100\%$ discharge. Also shown are classical slowing down calculations of beam ion densities and neutron rate. Although the beam ion density at the outer radius is in rough agreement throughout the discharge, the beam ion density at the inner radius does not increase as the neutral beam power increases, suggesting anomalous spatial redistribution of beam ions from the core. When we apply an anomalous diffusion [with an ad hoc beam ion diffusivity shown in Fig. 4(a)] in the TRANSP Monte-Carlo slowing down calculations, the calculated beam density profile is significantly reduced in the core compared to the case with classical slowing down. This results in a significant flattening of the NBCD profile in the core region. Applying the same model to the discharge that we are discussing, a flatter NBCD would reduce the structure in the inductive current

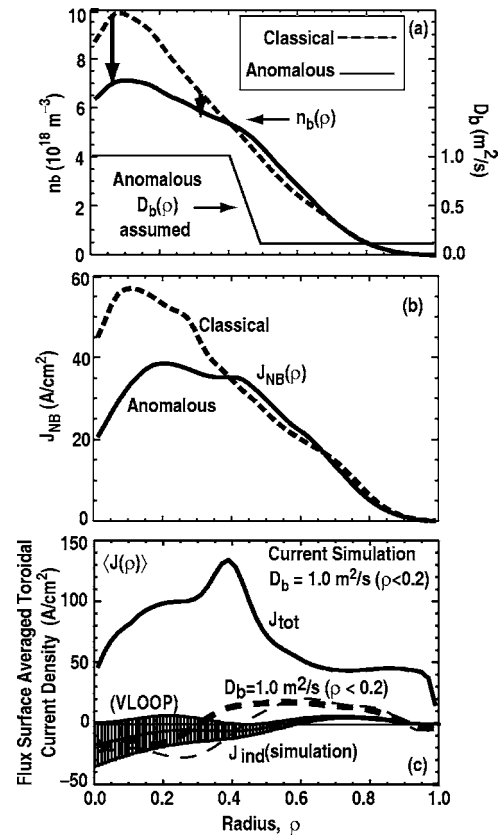


FIG. 4. Studies of impacts of the measurements on NBCD modeling; (a) the anomalous fast ion diffusivity assumed, and beam ion densities calculated for classical and anomalous beam slowing down; (b) calculated NB CD profiles for classical and anomalous slowing down calculation. Inductive current profile (bold dash) derived from neutral beam current drive model taken into account of anomalous beam ion diffusion assumed in (b) compared with inductive current profile (fine dash) with more conventional anomalous diffusion assumption and that derived from the equilibrium measurement (solid with error bars).

profile as shown in Fig. 4. In addition, the calculated neutron rates and stored energy using the anomalous diffusion agree better with the measurements.

The other possible explanation is inaccuracy in the bootstrap current calculation which is rather sensitive to input profiles (particularly electron density) near the center. Despite our best efforts to obtain electron density profiles consistent among measurements from Thomson scattering, reflectometer, and electron cyclotron emission (ECE) radiometer cutoff conditions, $\pm 10\%$ uncertainty in the bootstrap current in the inner half of the plasma remains. Together with uncertainties in the bootstrap current models, the accuracy of the inductive current calculations are estimated to be limited to $\pm 10\%$ in local and $\pm 5\%$ in the integrated values. Nevertheless all of these methods of analysis indicate that, to within the uncertainty, fully noninductive conditions have been obtained.

In this discharge, sustainment of the 100% noninductive condition was limited by the plasma pressure evolution rather than the current evolution. As shown in Fig. 5, pressure peaking (primarily due to density peaking) increased as β_N increased. At $\beta_N = 3.3$, the calculated wall position for $n = 1$ marginal stability reached the DIII-D conformal wall po-

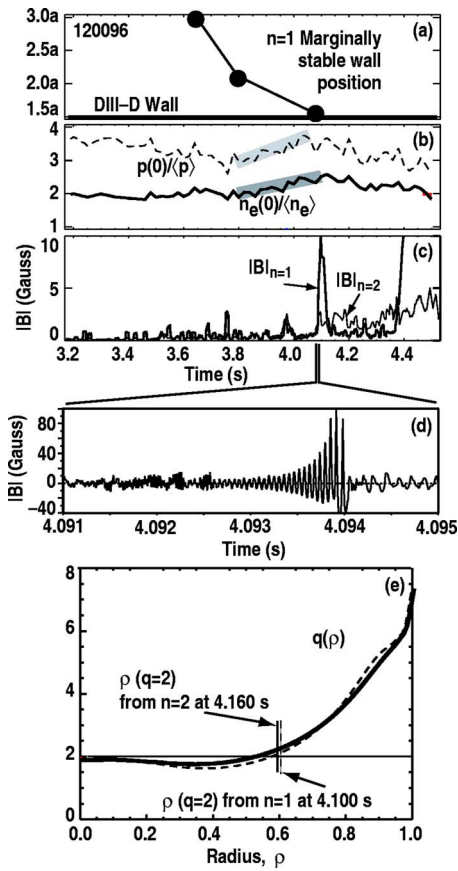


FIG. 5. Pressure profile evolution to MHD unstable state of the 100% noninductive fraction discharge shown in Fig. 1, (a) wall positions for $n=1$ marginal stability calculated by GATO stability code; (b) density and pressure peaking factors; (c) magnetic perturbation of $n=1$ and 2; (d) fast growing $n=1$ mode; and safety factor profiles and the positions of $q=2$ determined by the origins of the fast growing modes.

sition $(1.45a)$.⁹ At that point, we observed an $n=1$ fast growing mode that triggered $n=1$ neoclassical tearing modes. Even at β_N near the ideal wall limit, the high-performance phase almost always ends as a result of a tearing mode rather than a kink mode.

In a separate discharge, a nearly full noninductive, stationary discharge was obtained, which was limited only by the ECCD source. Time histories of pitch angles of individual motional Stark effect (MSE) diagnostic channels²⁵ are very stationary, indicating that the total current profile stopped evolving.²⁶ In this discharge $f_{NI} > 90\%$ lasted for 1.8 s, about one current relaxation time (τ_{CR}), at $\beta_T = 3.7\%$, $\beta_N = 3.5$, and $q_{95} = 5.1$. This current relaxation time²⁷ is defined as the time constant of the lowest order spatial eigenmode of the current evolution equation with the constraint of constant current, $\tau_{CR} = 0.17R/\mathfrak{R}$, where R is the plasma major radius in meters and $\mathfrak{R}$ is the plasma resistance in $\mu\Omega$. The normalized fusion performance (G) for this discharge is 0.3 with bootstrap current fraction of 60%. Therefore the performance level required for the ITER steady-state scenario was achieved. However, we have to point out that there are substantial differences in plasma conditions between the present experiments and ITER (for example, T_i/T_e , rotation, etc.). This motivates us to continue to work on using im-

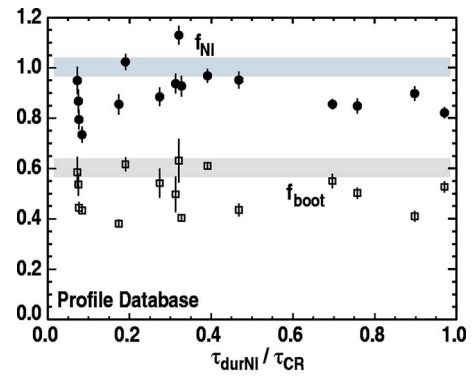


FIG. 6. Noninductive current (solid) and bootstrap current (open) fractions as functions of noninductive duration normalized to current relaxation time in the profile database. Here the noninductive duration is the period of noninductive fraction above 85% the peak noninductive fraction in each discharge, and values and error bars of the noninductive and bootstrap fractions are calculated over the period.

proved hardware that will allow us to access to the more ITER-relevant regime.

III. OPTIMIZATION FOR FULL NONINDUCTIVE, HIGH β OPERATION

Optimization of fully noninductive, high beta operation can be explored by studying the detailed characteristics of a few discharges and also by studying trends with various plasma parameters in a database containing a large number of such discharges. We have assembled two databases from these experiments: a profile database and a global parameter database. The profile database stores the detailed parameters for about 15 discharges whose characteristics have been studied in detail using time-dependent TRANSP analysis. Figure 6 shows results of the profile database indicating noninductive conditions with $\sim 60\%$ bootstrap fraction have been sustained up to one current relaxation time (τ_{CR}). A typical value of τ_{CR} is 2 s in these discharges.

The global parameter database contains about 160 shots whose primary selection criteria are:^{28,29} the duration of β_N above 85% of the maximum β_N is longer than five energy confinement times or 0.7 s, whichever is longer; $\beta_N > 2$; and $H_{89} > 2$. All parameters are time averaged over the period of $\beta_N > 85\%$ of the maximum β_N . One of the most useful parameters in this database is the average noninductive current fraction, $\langle f_{NI} \rangle$, which is equal to $1 - \langle V_{surf} \rangle / \langle \mathfrak{R} \rangle I_p$, where $\langle V_{surf} \rangle$ is the average surface voltage, and $\langle \mathfrak{R} \rangle$ is the average plasma resistance. Note that different averaging processes result in slightly different estimates of noninductive fraction in the two different databases. Comparing the noninductive fractions indicates that the global noninduction fraction underestimates by $\sim 6\%$ relative to that in the profile database. Figure 7 shows a large number of discharges have attained the conditions required for the ITER steady-state conditions ($G=0.3$ and $\langle f_{NI} \rangle = 1$). Figure 8 shows the average noninductive fraction as a function of β_N for two different values of q_{95} (5.0 and 5.5) in this database. These data show that the noninductive fraction increases strongly with β_N for a given q_{95} . Although $\langle f_{NI} \rangle$ also increases strongly with increasing

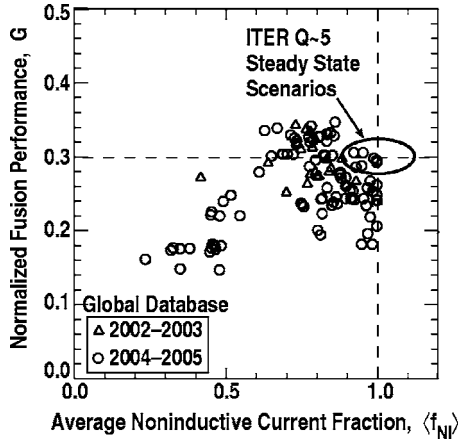


FIG. 7. Normalized fusion performance versus average noninductive current fraction in the DIII-D global database. Here the average noninductive current fraction are calculated based on the average surface voltage and plasma resistance. Growing numbers of shots are approaching the ITER steady-state scenario target.

q_{95} , operating with a higher q_{95} substantially compromises the fusion performance, $G = \beta_N H_{89} / q_{95}^2$. Studies^{2,7} have shown q_{95} must stay close to 5 to maintain adequate G .²

The choice of the plasma density is important for optimization of the noninductive operation. Figure 9 shows the dependencies of the noninductive current components as a function of line average density based on a set of density scan discharges in the profile database. The overlaid curves are results of simulations using the GLF23 model (discussed later) for a fixed density shape of one of the shots (111221). The curves represent well the trend of the fractions of noninductive current components, validating CD source models. The bootstrap current is observed to increase with density, but more slowly than NBCD and ECCD decrease. The net result is that the noninductive current fraction decreases with density, and thus noninductive current is maximized at lower density. A measure of the current drive alignment can be estimated using a CD alignment figure of merit:⁷

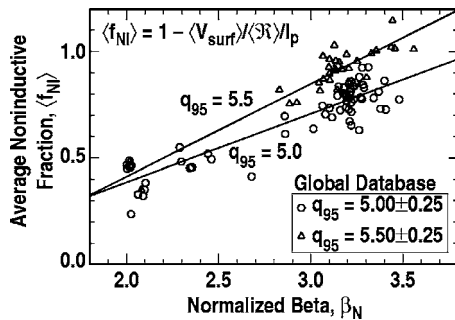


FIG. 8. Average noninductive current fraction as a function of normalized beta for two different safety factor, $q_{95} = 5.0$ and 5.5 , in the global database. The average noninductive current fraction depends strongly on the normalized beta (approximately as $\langle f_{NI} \rangle \propto \beta_N^{1.4}$). The dependence on q_{95} is almost as strong as β_N .

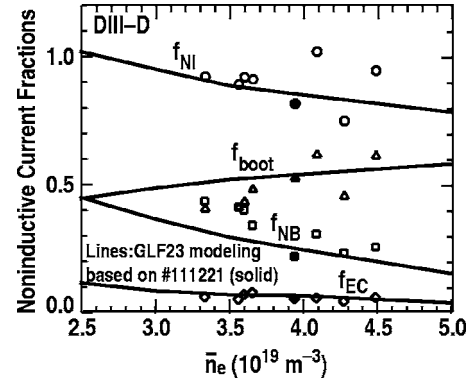


FIG. 9. Noninductive current fraction (circle), and its components: bootstrap current (triangle), neutral beam current drive (square) and electron cyclotron current drive (diamond), as functions of line average density in the density scan in DIII-D based on TRANSP profile analysis. The solid curves are results of transport simulations using the GLF23 model with scaled densities based on the discharge with a 85% noninductive case (solid symbols).

$$\xi_{\text{tot}} = 1 - \frac{\int (n_e / T_e) |J_{\text{ind}}| dA}{\int (n_e / T_e) |J_{\text{tot}}| dA}.$$

This figure of merit measures the relative amount of additional current drive power that will be required to achieve full CD alignment. Both f_{NI} and the CD figure of merit are reduced at high density, which indicates the CD alignment is poor in a region where it is difficult to drive current, i.e., at larger radii. Low density discharges are much better in this regard.

IV. SCENARIO MODELING

A. Validation

Close coupling between modeling and experiment is key to understanding complex interactions between bootstrap current, external current drive, transport and MHD stability and their integration into self-consistent high-performance scenarios in the experiments. Both empirical and theory-based transport models are used to plan and interpret these experiments. These comparisons validate the models to allow their use in planning future DIII-D experiments. The gyro-Landau-fluid (GLF23) model¹⁴ implemented in the ONETWO transport code³⁰ is the primary tool in this experiment. Validation of this model was carried out against one of the fully noninductive, high β discharges. The experimental data in Fig. 10 were chosen to be at the same phase (60%-80%) in the ELM cycles in a stationary part of the discharge using the tools developed for pedestal studies.³¹ The GLF23 model^{14,32} uses drift-wave eigenmodes to compute the quasilinear energy, toroidal momentum fluxes due to ion/electron temperature gradient (ITG/ETG) and trapped electron modes (TEM). The model includes $E \times B$ shear and alpha stabilization using the predicted profiles. The electron and ion turbulent diffusivities from GLF23 are added to the neoclassical diffusivities, while the toroidal momentum transport is added to an ad hoc enhancement, taken in this case to be twice the neoclas-

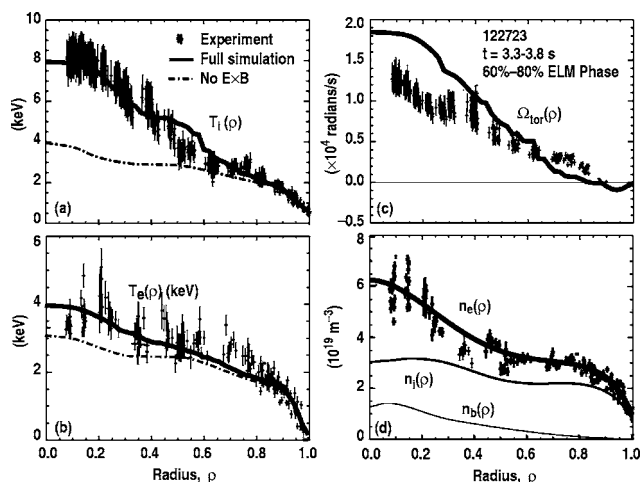


FIG. 10. Comparison of profiles of (a) ion temperature, (b) electron temperature, and (c) toroidal angular velocity from experimental measurements and predictions of the GLF23 model based on (d) the density profiles and the respective profiles as initial conditions and boundary conditions imposed at $\rho=0.9$. The experimental data were chosen to be the same phase (60%–80%) in the ELM cycles in a stationary part of a fully inductive discharge.

sical ion thermal diffusivity.³² In this simulation, the electron temperature (T_e), ion temperature (T_i), poloidal magnetic field (current density), toroidal momentum, and equilibrium evolution are solved with self-consistent source and sink calculations by time stepping from initial profiles for about $0.5 \tau_{CR}$. The GLF23 model reproduces experimental profiles reasonably well, as seen in Fig. 10. An exception is an overestimate of the toroidal rotation in the core. An empirical multiplier larger than two on the ion thermal neoclassical diffusivity in the toroidal momentum equation would improve the agreement with the experimental toroidal rotation data. Simulation without $E \times B$ shear stabilization leads to a substantially lower ion temperature [Fig. 10(a)], indicating the importance of the rotation, while the alpha (Shafranov shift) stabilization plays a minor role.

B. DIII-D simulation

Predictive simulations with the GLF23 model indicate that 100% noninductive operation at higher β will be possible using hardware improvements being made on DIII-D.³³ As presented in Fig. 9, the GLF23 model reproduced well the trends of the noninductive current components in the density scan data based on density profiles scaled from that of a single-null discharge, serving a validation test of the model against the density scan data. Figure 11 extracts the results of the modeling. Similar dependencies were found for existing higher-density double-null divertor (DND) discharges without pumping. Replacing the flat density profile with a peaked density profile, expected from DND operation with pumping, would increase the noninductive fraction. The DN pumped divertor configuration will allow operation with density control in an optimized shape for improved stability at high β .⁹ A GLF23 simulation indicates that 100% noninductive, high β conditions can be obtained with 4.5 MW of ECCD deposited around $\rho \approx 0.6$ and 3.5 MW of fast wave (FW) heating and current drive.²⁶ Higher FW power, allow-

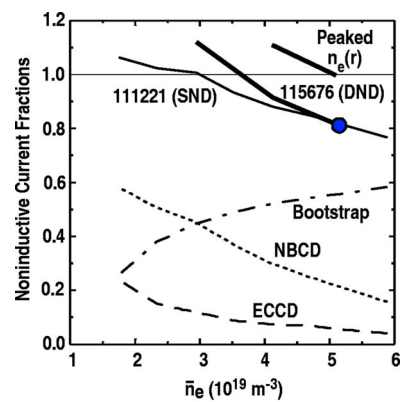


FIG. 11. Density dependence of the noninductive current fractions predicted for double-null divertor (DND) discharge by the GLF23 model based on existing profiles of unpumped DND discharge. The noninductive fraction for DND discharge with peaked density profile with pump is predicted to be higher. The overlaid curves for the noninductive current fractions and their components are those for single null discharges shown in Fig. 9.

ing lower NB heating and current drive power, should facilitate operation with $T_e \approx T_i$, a more relevant regime for next-step burning plasmas. Finally, two (out of seven) NBI sources have been reaimed in the counter direction. This will give added flexibility by allowing us to vary the co/counter mix of NBI sources, thereby modifying both NB H/CD and rotation. Higher NB heating power will be available without beam overdrive in the core with the appropriate co/counter beam mix, allowing exploration of the stability boundaries of full noninductive operation at high beta.

C. ITER simulation

The modeling tools that were successfully employed to devise experiments in DIII-D, when applied to ITER, indicate fully noninductive operation is plausible for an ITER steady-state scenario with $Q \approx 5$ with Day-1 hardware capabilities.³⁴ Previously we showed an “existence proof” of full noninductive operation at $Q \approx 5$ at high density ($N_{GW} = 1.25$) using the GLF23 model^{26,34} with the ITER Day-1 hardware capabilities.³⁴ Here we evaluate how the noninductive operation would change when the plasma density is varied as in DIII-D. Each simulation was evolved for 100 s, which is about $1 \tau_{CR}$ for ITER, to follow the evolutions of T_e , T_i , toroidal rotation, current density and equilibrium with a fixed density profile using the theory-based (GLF23) model with self-consistent sources and sinks. Fractions of the noninductive current components and fusion gain, Q , are plotted as a function of Greenwald number (Fig. 12). The trend of the noninductive current fractions are reminiscent of those for the DIII-D density scan. Increased noninductive fraction above 100% is attained at $N_{GW} \approx 1$ with Q (nearly equal) 5. Table I tabulates a self-consistent set of the parameters corresponding to the $N_{GW}=1$ case, attaining $f_{NI}=100\%$. This suggests that a steady-state solution exists with $Q=5$.

This work is still in progress. Some important advanced tokamak physics issues that have to be addressed include consistency of the pedestal temperature, the density profiles,

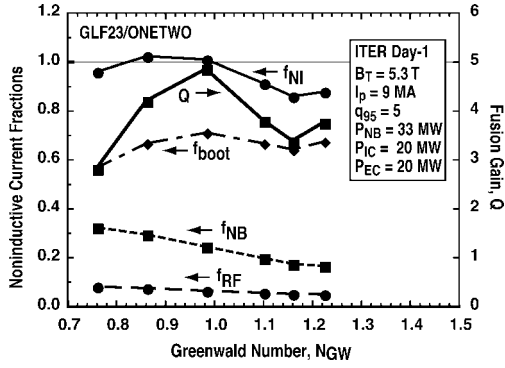


FIG. 12. Density dependences of the noninductive current fraction and its components, bootstrap current, neutral beam and rf (ion cyclotron and electron cyclotron current drive combined), and fusion gain predicted by the GLF23 model using the ITER Day-1 hardware capabilities. The electron density is expressed by the Greenwald density number.

MHD stability, and the divertor heat load and stability. We would like to point out some of the caveats regarding the present modeling:

1. The edge temperature used in the above modeling is based on the edge temperature required for generating the $Q=5$ ITER steady-state scenario using the specific theory-based model.³⁶ As such it is not based on any edge physics model. Therefore the validity of the edge temperature needs to be investigated. The temperature fixed at $\rho=0.9$ seems high ($T>7.2$ keV), but the value of β where the boundary conditions were imposed in the simulation is only slightly above the DIII-D case (1.3% vs 1.0%).
2. The density profile used in the present modeling originates from the one used in an earlier ITER simulation study as a density profile similar to that of a DIII-D AT discharge.³⁷ The large density “pedestal” width assumed in the simulation, and observed in the experiment, gives a larger stability margin for peeling-ballooning modes.³⁷ It is our plan to include the density equation in the GLF23 model.
3. The target $\beta_N \approx 2.8$ calculated is above the beta limit against the $n=1$ mode without conducting wall ($\beta_N^{\text{no-wall}} \approx 2.4-2.5$).^{37,38} Although the predicted central

TABLE I. ITER steady-state conditions obtained with $N_{GB} \approx 1$, $f_{NI} \approx 100\%$ in the density scan of ONETWO simulation using GLF23 model. H_{98y2} is the ratio of energy confinement relative to ITER H-mode scaling.³⁵ G is the normalized fusion performance, $\beta_N H_{89} / q_{95}^2$.

P_{NB} (MW)	33	f_{BS} (%)	70.7
P_{IC} (MW)	20	f_{NB} (%)	24.0
P_{EC} (MW)	20	f_{IC} (%)	3.7
B_T (T)	5.3	f_{EC} (%)	2.2
I_p (MA)	9.0	f_{NI} (%)	100.6
q_{95}	4.9	β_N	2.7
N_{GW}	0.99	H_{89}	2.6
Q	4.8	H_{98y2}	1.5
β_T (%)	2.5	G	0.29

plasma rotation frequency is about 2.5% of the Alfvén frequency, uncertainties in the simulation (e.g., empirical addition of the neoclassical ion thermal diffusivity in the momentum diffusivity) make it unclear whether it is sufficient to provide RWM stabilization without an active feedback system. The forthcoming DIII-D experiments with the external and internal control coils and capability to produce nonrotating high beta plasmas using co- and counter NBI will provide opportunities to study effectiveness of feedback stabilization under more ITER-relevant conditions.

V. CONCLUSIONS

One hundred percent noninductively driven plasmas were obtained with good CD alignment at $\beta_T \leq 3.6\%$, $\beta_N \leq 3.5$ and $H_{89}=2.4$. The duration was limited to $\sim 0.5\tau_{CR}$ by pressure profile evolution to unstable MHD. The current balance calculation improved with beam ion redistribution that was supported by the recent fast ion diagnostic measurements. Nearly ($\sim 90\%$) noninductive, stationary discharges were sustained for $1\tau_{CR}$ and were only limited by present hardware limits. These experiments have achieved normalized fusion performance $G=0.3$ and $f_{BS}=60\%$, which is consistent with requirements for the ITER $Q=5$ steady-state scenario. With good coupling between experiment and modeling, progress has been made in identifying the need for low density and other optimizations for noninductive operation and current drive alignment. Future plans of DIII-D include exploring stability boundaries using more EC and FW power with longer duration, double-null divertor with pumping and co + counter NBI. Modeling tools that were successfully employed to devise experiments in DIII-D, when applied to ITER, indicate full noninductive operation is conceivable for steady-state operation with $Q \approx 5$. The scientific basis being developed on DIII-D is leading to increased confidence in establishing steady-state scenarios for ITER and beyond.

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