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Progress Toward Fully Noninductive, High Beta Discharges in DIII–D

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Abstract. Advanced Tokamak (AT) research in DIII-D focuses on developing a scientific basis for steady-state, high performance operation. For optimal performance, these experiments routinely operate with β above the n=1 no-wall limit, enabled by active feedback control. The ideal wall β limit is optimized by modifying the plasma shape, current and pressure profile. Present DIII–D AT experiments operate with f_{BS}≈50%–60%, with a long-term goal of ~90%. Additional current is provided by neutral beam and electron cyclotron current drive, the latter being localized well away from the magnetic axis (ρ≈0.4–0.5). Guided by integrated modeling, recent experiments have produced discharges with β≈3%, β_N≈3, f_{BS}≈55% and noninductive fraction f_{NI}≈90%. Additional control is anticipated using fast wave current drive to control the central current density.

1. The DIII–D Advanced Tokamak Research Program

There is little doubt that conventional tokamak operating scenarios anticipated for operation of next-step devices such as ITER will produce sufficient fusion performance, albeit with pulsed operation. Advanced Tokamak (AT) research at DIII–D seeks to develop a scientific basis for steady-state operation of such devices without sacrificing fusion performance. This raises several challenges: Steady-state operation requires the plasma current to be driven noninductively. High bootstrap current fraction $f_{BS} = I_{BS}/I_P \propto \beta_P \propto q\beta_N$ minimizes the recirculating power. High fusion performance requires high β_T. Realizing these conditions simultaneously demands operation at high $\beta_N = \beta_T a B_T / I_P$ and τ_E.

This demands advanced understanding and control of stability, transport, current drive and the boundary. High β_N operation requires optimization of the plasma geometry and pressure profile shape. The kinetic profiles determine the bootstrap current, both to maximize f_{BS} and match the desired current profile shape. Both stability and current profile control are then coupled to transport physics. External sources supplement the bootstrap current, eliminating the need for Ohmic current drive. The primary source of this current in DIII-D is electron cyclotron current drive (ECCD). Electron cyclotron (EC) driven current is maximized at low density, necessitating effective particle control.

An additional challenge is that advances in each of these areas must be integrated into a single operating scenario. Design of DIII-D AT experiments uses results from both previous experiments and an extensive integrated modeling effort. In this way, the experiments and the models themselves advance together. A sophisticated plasma control system, under continued development, allows simultaneous control of the diverse elements of these efforts.

Recent progress focuses on two areas: First, using ECCD, AT discharges have been sustained with the noninductively driven current fraction $f_{NI} \leq 90\%$ and $\beta_N \leq 3.1$ [1]. Second, the dependence on plasma shape of the achievable β in these AT plasmas has been studied and may motivate future modifications.

2. Near Steady-State Operation

The plasmas discussed here are produced by inducing an L–H transition early during the current ramp, facilitating high T_e in the core and slowing the q profile evolution. This produces target plasmas with $q_{min} > 2.5$ at 1.5 s or $q_{min} > 1.5$ at 3.0 s. All experiments discussed here were carried out with I_P = 1.2 MA, B_T = 1.85 T and q_{95} = 4.9.

Prior to initiating ECCD, the NBI power is increased and feedback controlled to maintain $\beta_N \approx 2.8$, above the no-wall stability limit, but still below the achievable limit. Most of the current is supplied by a combination of bootstrap and neutral beam current drive (NBCD). The remaining Ohmic current is concentrated near the mid-radius. ECCD is injected into this region to replace this Ohmic current. The EC launchers are steerable to allow control of both the radial position and toroidal angle of the injected waves, allowing comparisons of discharges with electron cyclotron heating (ECH) (heating only; no current drive), ECCD, and NBI only (Fig. 1). As predicted by integrated modeling, q_0 increases radically, while a small decrease is seen in q_{min}, so that the q profile develops a region of strong negative shear in the vicinity of the magnetic axis. This leads to formation of an internal transport barrier, evident in the temperature profiles.

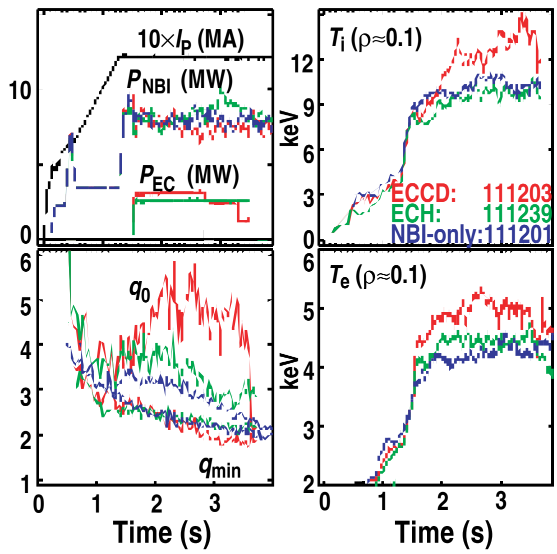

Fig. 1. Both heating and current drive effects are seen when off-axis ECCD is injected into an AT discharge. The current and temperature profiles are strongly modified in a discharge with ECCD, with smaller changes seen when the EC waves are injected radially with no current drive.

Simulations of these discharges have been carried out using a 1-1/2 D transport code, TRANSP, with EC heating and current drive calculated by a linear ray tracing code (TORAY-GA). Bootstrap current is calculated by the Hirshman 78 model. The resulting current profiles, both with ECCD and ECH, are calculated and are in good agreement with those measured by the motional Stark effect (MSE) diagnostic (Fig. 2). These calculations indicate that approximately 90% of the plasma current was maintained by noninductive means for the duration of the full power ECCD.

Since $f_{BS} \propto q\beta_N$, operation at lower q values may be acceptable if higher β is accessible. We have previously reported reductions in the achievable β at high q_{min} [2]. In discharges similar to those described above, $f_{NI} \approx 90\%$ was obtained in a nearly stationary plasma for

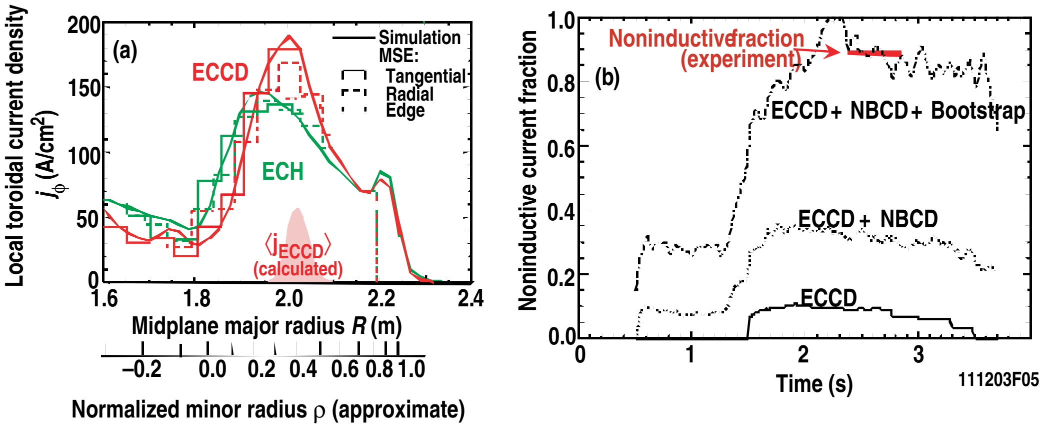

Fig. 2. (a) Simulated current profiles with and without ECCD are in good agreement with measurements using MSE, and indicate that ECCD drives 130 kA in this discharge. (b) EC driven current, in combination with neutral beam current drive and bootstrap current, provides approximately 90% of the total current.

1.0 s with $\beta_N \approx 3.1$. Simulations based on these discharges (Fig. 3) indicate sustainment of similar discharges, with higher β, should be possible with presently available hardware. Other simulations indicate fast wave current drive (FWCD) may be effective at controlling the current density near the magnetic axis, allowing the plasma to rapidly reach a well-controlled steady state.

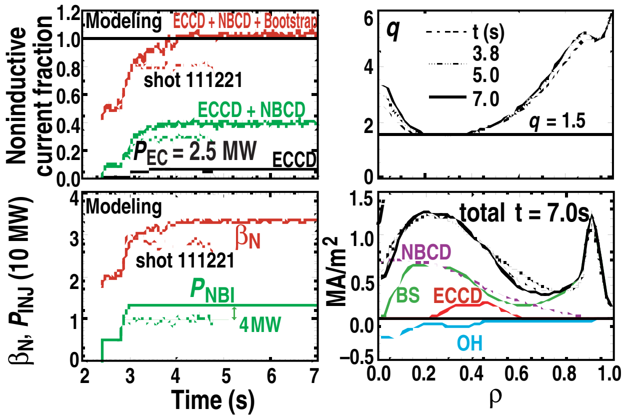

Fig. 3. Simulations based on the $q_{min} > 1.5$ discharge predict sustainment with $f_{NI} \approx 100\%$ with the present DIII-D hardware configurations.

3. Operation at High Beta

High β operation is beneficial in these plasmas, both for its impact on f_{BS} and to maximize fusion performance. DIII–D AT discharges routinely operate above the no-wall β limit, using feedback control to reduce error fields and enhance rotational stabilization, and in the future to directly stabilize resistive wall modes [3]. Neoclassical tearing modes [4], which often limit performance, are expected to become less important as f_{NI} approaches 100% and the q profile becomes stationary.

Two important factors have been identified in determining this limit. The broadness of the pressure profile is critical, with stability improving as $p_0/\langle p \rangle$ is reduced [5]. This is particularly the case in strongly shaped (high triangularity and elongation) plasmas such as those in DIII–D. Our ability to control the pressure profile is very limited, since it is largely determined by the current profile control tools themselves.

The experiments discussed above are executed in single-null divertor plasmas with moderately strong shaping: elongation $\kappa \approx 1.8$ and triangularity $\delta \approx [0.65,0.45]$ (upper, lower). This shape is chosen for its ability to couple to a cryopump in the upper divertor, facilitating the effective density control [6] needed to maximize EC driven current (Fig. 4). However, the highest β values obtained experimentally are in more strongly shaped plasmas.

Recent efforts have focused on determining the effect of plasma shape on achievable β. Numerical studies [7,8] suggest some advantage to a balanced double-null divertor configuration with stronger shaping. An experiment was carried out in which NBI was added to rapidly increase β in unpumped plasmas with a variety of shapes. The maximum achievable β, believed to be closely related to the no-wall limit, increased with the shaping parameter $S = q_{95}I_P/aB_T$ (Fig. 5). Results of these studies motivate consideration of divertor modifications to provide density control in higher triangularity double-null divertor plasmas.

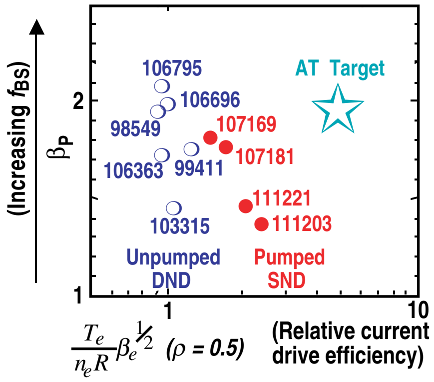

Fig. 4. Double-null plasmas access the highest β values, but the lack of density control reduces ECCD efficiency.

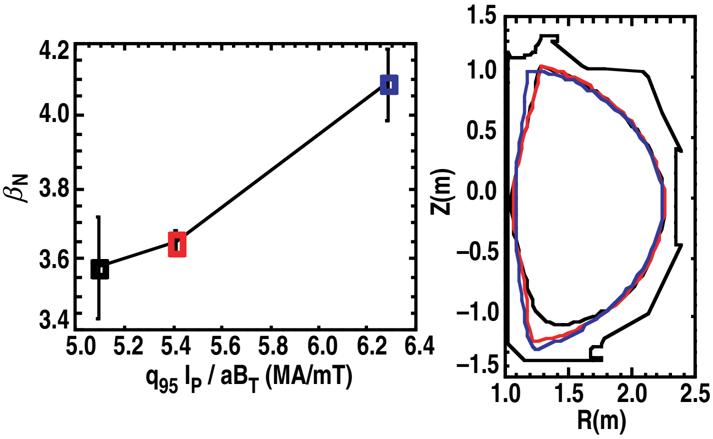

Fig. 5. Achievable β limit increases with shaping. The upper single-null shape (black) is that used for the experiments which reached $f_{NI} \approx 90\%$.

4. Discussion

These experiments are part of a long-term program aimed at establishing a scientific basis for steady-state high performance regimes. Integration is a critical element of this effort. Numerous control tools (those discussed here are a subset) are used simultaneously, each affecting multiple characteristics of the plasma. Achievement of $f_{NI} \approx 90\%$ at $\beta_N \approx 3$ is an interim demonstration of successful integration. Further work will incorporate continued development of these and other tools to obtain $f_{NI} \approx 100\%$ at higher β. We look forward not only to demonstration of steady-state regimes at the highest levels of performance, but also to the creation of a fully predictive capability to design AT regimes for next-step devices.

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