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J.R. FERRON, V. BASIUK,* T.A. CASPER,† J.C. DeBOO, E.J. DOYLE,‡ Q. GAO,§ A.M. GAROFALO, C.M. GREENFIELD, C.T. HOLCOMB,† T.C. LUCE, M. MURAKAMI,# Y. OU,¶ C.C. PETTY, P.A. POLITZER, H. REIMERDES,◊ E. SCHUSTER,¶ M. SCHNEIDER,* and A. WANG‡

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*Association Euratom-CEA, CEA-Cadarache, St. Paul lez Durance, France.
†Lawrence Livermore National Laboratory, Livermore, California.
‡University of California-Los Angeles, Los Angeles, California.
§Southwest Institute of Physics, Chengdu, China.
#Oak Ridge National Laboratory, Oak Ridge, Tennessee.
¶Lehigh University, Bethlehem, Pennsylvania.
◊Columbia University, New York, New York.

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Development in DIII-D of High Beta Discharges Appropriate for Steady-State Tokamak Operation With Burning Plasmas Ex-S

J.R. Ferron,[1] V. Basiuk,[2] T.A. Casper,[3] J.C. DeBoo,[1] E.J. Doyle,[4] Q. Gao,[5] A.M. Garofalo,[1] C.M.Greenfield,[1] C.T. Holcomb,[3] T.C. Luce,[1] M. Murakami,[6] Y. Ou,[7] C.C. Petty,[1] P.A. Politzer,[1] H. Reimerdes,[8] E. Schuster,[7] M. Schneider,[2] and A. Wang[5]

[1]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
[2]CEA-Cadarache, Cadarache, France
[3]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[4]University of California, Los Angeles, California 90095, USA
[5]Southwest Institute of Physics, Chengdu, China
[6]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[7]Lehigh University, Bethlehem, Pennsylvania 18015, USA
[8]Columbia University, New York, New York, USA

A research focus at DIII-D is development of methods for reliable production of high beta discharges suitable for high fusion gain power plant operation with 100% of the plasma current generated noninductively (f_{NI} = 1). Included in this work is validation of the physics basis necessary to confidently design next-step tokamaks for steady-state operation. Recent work has encompassed a complete discharge scenario, from feedback control of the q profile evolution during the initial, low beta, discharge formation phase to the optimization of the discharge shape and electron cyclotron current drive (ECCD) deposition profile for stable, stationary operation at maximum β_N of the f_{NI} = 1 phase of the discharge. In addition, experiments to increase β_N to 4-5 with profiles suitable for steady-state operation have begun, motivated by the requirement for high power density and neutron fluence in a demonstration power plant. Two approaches capable of reaching β_N = 5 have been identified through modeling and tested experimentally: a wall-stabilized scenario with q_{min} > 2 and a high internal inductance (l_i) scenario that maximizes the ideal no-wall stability limit.

The maximum achievable β_N in steady-state scenario discharges is typically produced with a double-null divertor shape, but in recent experiments H_{89} has been shown to increase by up to 20% with the shape biased toward single null with the X point located opposite the direction of the ion ∇B drift (Fig. 1). This improved confinement along with newly expanded ECCD capability (3 MW for 5 s) enabled operation with a stationary current profile for one resistive time (τ_R) with f_{NI} = 0.9, β_N = 3.4, H_{89} = 2.3, H_{98y2} = 1.4 and G = $\beta_N H_{89}/q_{95}^2$ = 0.3, which projects to Q = 5 in ITER. The estimated bootstrap current fraction is 60%. Transport code simulations, validated against the experiment, indicate that stationary f_{NI} = 1 discharges will be accessible with combinations of increased β_N, the planned additional ECCD power and application of fast wave current drive. An increase in the maximum stationary

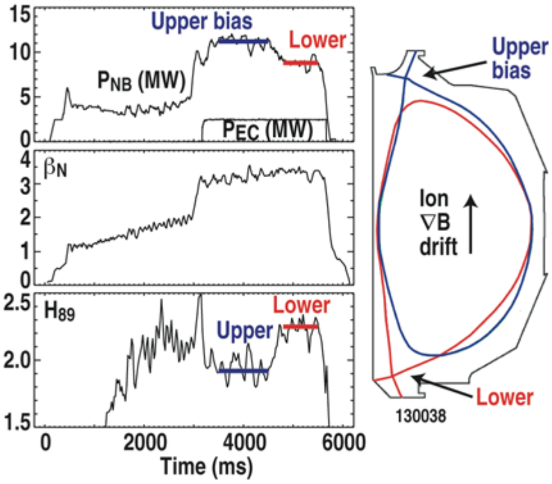

Fig. 1. The change in normalized confinement (H_{89}) observed when the up/down bias of the shape is varied in a steady-state scenario discharge (upper biased 3400-4600 ms, lower biased 4800-5500 ms). During the high-performance phase of the discharge (3000-5600 ms), β_N is maintained by feedback control, so changes in confinement are reflected in changes in the required neutral beam power (P_{NB}).

β_N stable to the 2/1 tearing mode was achieved by varying the ECCD deposition profile (peaked at ρ=0.4 or 0.5, distributed between ρ = 0.35 and 0.55). In all three cases, β_N = 3.2 was stable for τ_R but only the case with the broad deposition profile was stable at β_N = 3.4.

Closed loop feedback control of the evolution of q_{min} during the plasma current (I_p) ramp up and early flattop is used to set the value of q_{min} at the start of the high β_N phase. Proportional/integral gain control is used to calculate the required neutral beam power (P_{NB}) which can vary the rate of evolution of the current profile by changing T_e, and, thus, the conductivity. Open loop measurements of the q profile evolution have been compared to transport code simulations (Fig. 2) in order to validate the models for poloidal flux evolution and neutral beam current drive. As a step toward development of model-based controllers, which will be essential in devices such as ITER, a simplified model of poloidal flux diffusion has also been tested against the experiment.

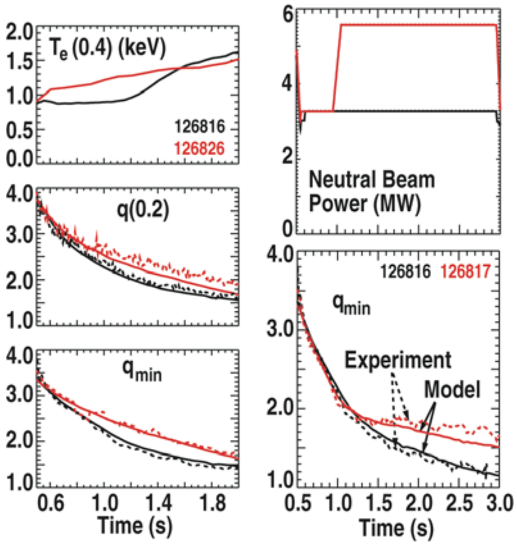

Fig. 2. Comparisons between experiment (dashed) and simulation (solid) using the ONETWO transport code of the q evolution during the I_p ramp up and early flattop. Left column: At two different levels of T_e, varied using ECH heating. Right column: Response of dq_{min}/dt to a step in P_{NB}.

Model predictions that β_N = 5 can be accessed in discharges with elevated l_i = 1.1-1.5 without requiring wall stabilization have been tested transiently thus far up to β_N = 4.6 (β_T = 4.8%, l_i = 1.1, Fig. 3). Discharges were created using the ITER startup technique with breakdown at the outer wall limiter and elongation and current rampup at constant q_{95} with little auxiliary heating in order to maximize current penetration and thus l_i. β_N was ramped up under feedback control to reach a stability limit, which resulted either from tearing modes or a fast growing internal instability. MHD spectroscopy measurements indicate that β_N remained below the ideal, n=1 no-wall stability limit, as expected. Confinement was improved over a standard H-mode with H_{89} = 2.7 (H_{98y2} = 1.5).

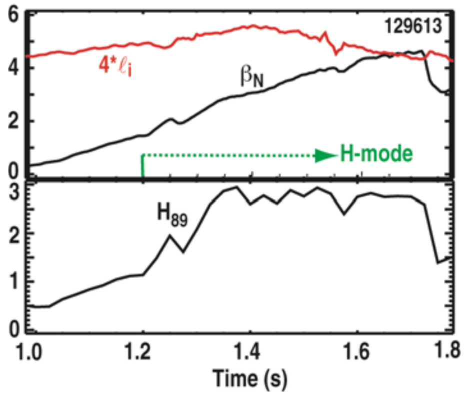

Fig. 3. Time evolution of a discharge with elevated values of l_i in which β_N = 4.6 was reached simultaneously with confinement 35% above the normal value for H-mode. The estimated no-wall stability limit is 4 l_i.

In the wall-stabilized approach to maximizing β_N, with q_{min} > 2 and a broad current profile, β_N = 4 has been achieved, but with q_{min} evolving below 2. Recent experiments focused on reduction of the on-axis neutral beam current drive with most neutral beam power injected in the direction opposite to the plasma current in order to maintain q_{min} above 2. Mode locking at low rotation limited β_N to approximately the no-wall limit. Future experiments will utilize sufficient neutral-beam-injected torque throughout the discharge to avoid a low rotation phase.

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