Neutral-Beam Current-Driven High–Poloidal-Beta Operation of the DIII-D Tokamak

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Neutral-beam current-drive experiments in the DIII-D tokamak with a single null poloidal divertor are described. A plasma current of 0.34 MA has been sustained by neutral beams alone, and the energy confinement is of *H*-mode quality. Poloidal β values reach 3.5 without disruption or coherent magnetic activity suggesting that these plasmas may be entering the second stability regime.

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The tokamak magnetic fusion configuration requires a toroidal current within the plasma. Generally this current is inductively coupled. Tokamaks can therefore only operate for finite-duration pulses. Also, the current concentrates in regions of high electrical conductivity (regions of high electron temperature) and thereby does not necessarily produce an optimum radial current profile. Numerous noninductive current-drive methods[1] have been proposed, including injection of electromagnetic waves and neutral beams. These methods could allow steady-state tokamak operation and optimization of the radial current profiles to possibly improve confinement and provide access to the second stability region, in which increasing plasma pressure increases plasma stability.

The concept of neutral-beam current drive was proposed by Ohkawa[2] and the basic principle was demonstrated in the Culham Levitron.[3] First tokamak results were obtained in DITE[4] and subsequently in TFTR[5] and JET.[6] This paper presents new results from the DIII-D[7] tokamak in which the plasma current was sustained entirely by neutral beams from 1.5 s without assistance from the Ohmic-heating transformer. After Ohmic startup, the Ohmic-heating-coil current was held constant so that the plasma current could freely adjust. This technique provides a striking demonstration of neutral-beam current drive. The poloidal beta, β_p, reached 3.5, raising the possibility that the plasma is entering the second stability region, as described later.

The DIII-D tokamak[7] was operated with a single-null-divertor configuration having a 1.70-m major radius, 0.6-m minor radius, 1.75 vertical elongation, and 2.1-T toroidal magnetic field. The experiments were carried out with a helium plasma having a line-averaged density $\bar{n}_e = 2\times10^{19}$ m^{-3}. Eight hydrogen neutral beams,[8] consisting of 52% neutral power at 75 keV, 30% at 37 keV, and 18% at 25 keV, were injected in the same direction as the plasma current. Four beams intersected the vacuum system axis at 47° and four beams intersected at 63°.

Plasma parameters are shown in Fig. 1 as functions of time. Initially, a 0.22-MA Ohmic discharge was established without sawteeth, indicating an on-axis safety factor $q_0 > 1$. At 1.1 s the Ohmic-heating-primary-coil current was held constant, so that without beam injection the plasma current decayed, as shown by the dashed line of Fig. 1(a). With 10 MW of absorbed neutral-beam injection [Fig. 1(b)], the plasma current increased to 0.34 MA. During the period when the current was sustained, the loop voltage [Fig. 1(c)] was zero, except for periodic voltage spikes associated with edge-localized-mode-like relaxation phenomena. Neutral-beam injection increased the total plasma energy as shown in Fig. 1(e). The similarity between magnetic and diamagnetic (DIAM) measurements indicates comparable parallel and perpendicular pressures as expected by the beam-injection geometry. The poloidal β, shown in Fig. 1(f), reached 3.5 ± 0.1.

An important aspect of these results is that the energy confinement was of *H*-mode quality with the noninductive current drive. The uncorrected 24-ms energy confinement time of this low-current, high-power discharge (72 ms/MA) is as good as the DIII-D *H*-mode scaling obtained with 8.4-MW hydrogen-beam injection into a deuterium plasma. The 24-ms energy confinement time is 2.4 times longer than Kaye-Goldston *L*-mode scaling,[9] although the density rise common to the *H* mode did not occur.

Charge-exchange-recombination-spectroscopy measurements of helium-ion temperature, shown in Fig. 2, indicate a central helium-ion temperature of 2.0 keV. The central rotation speed was 92 km/s, 2% of the injected-beam-ion speed. The Shafranov radial outward shift of the temperature profile agrees with magnetic measurements. The radial profile is narrower than commonly observed. Assuming the electrons to be the same temperature as the ions, we estimate that half of the plasma energy is attributable to energetic beam ions. The magnetically determined toroidal β is 0.5%.

We estimate the L/R time constant to be 2 s. Since the plasma current is essentially constant for 1.5 s, we conclude that the current is largely sustained by the neutral beams. Transport-code[10,11] studies of these discharges predict 0.3 to 0.4 MA of beam-driven current.

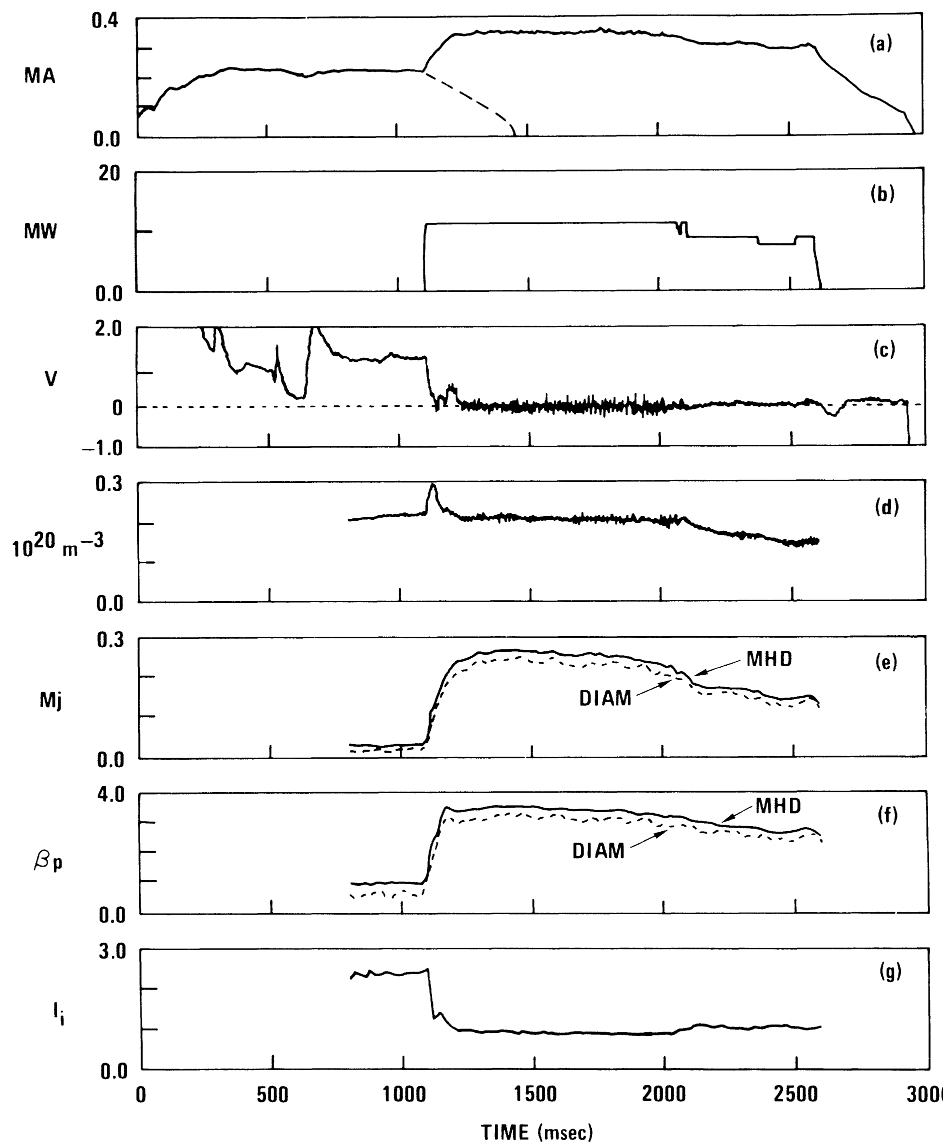

FIG. 1. Time dependence of (a) plasma current, (b) neutral-beam-injection power, (c) loop voltage, (d) line-averaged density, (e) plasma energy, (f) poloidal beta, and (g) internal inductance.

The bulk plasma bootstrap contribution is calculated to be only 10% to 20% because of the low 2-keV temperature ($\nu_* \sim 1$) and the broad radial density profile.

Several discharges with MHD $\beta_p > 3.4$ and diamagnetic $\beta_p > 3.0$ have been produced[12] without disruptions or coherent $n \neq 0$ modes. The $\beta_p = 3.5$ discharge shown in Figs. 1 and 2 has an inverse aspect ratio $\epsilon = 0.31$, so that $\epsilon\beta_p = 1.1$. While these values of β_p and $\epsilon\beta_p$ are among the highest achieved in a tokamak, they are not remarkable in themselves. What is remarkable is the absence of the large-amplitude MHD modes, observed in ISX-B[13] and Doublet III[14] at high β_p. As shown in Fig. 3, no sawteeth are present in the central soft-x-ray emission. Edge-localized modes similar to those observed at lower β_p are seen on the H_α emission in the divertor region, and on the soft-x-ray signals near the edge of the discharge. Despite the large β_p, moderately large ratio of toroidal β to I/aB, and large fast-ion population, the only coherent MHD activity observed on the magnetic probes is associated with the edge-localized modes. Except during the edge-localized-mode events, the amplitude of poloidal-magnetic-field oscillations measured at the wall is at most 0.1% of the total poloidal field.

Figure 4 shows EFITD magnetic analysis[15] of measurements from 41 flux loops distributed around the outside and 25 magnetic probes distributed around the inside

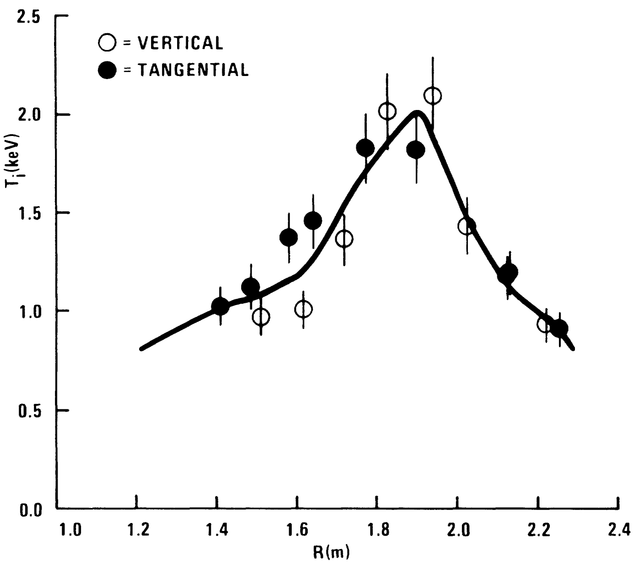

FIG. 2. Radial-profile measurements of helium-ion temperature at 1.4 s. Solid line is smooth fit to the data, with the assumption that ion temperature is constant on flux surfaces.

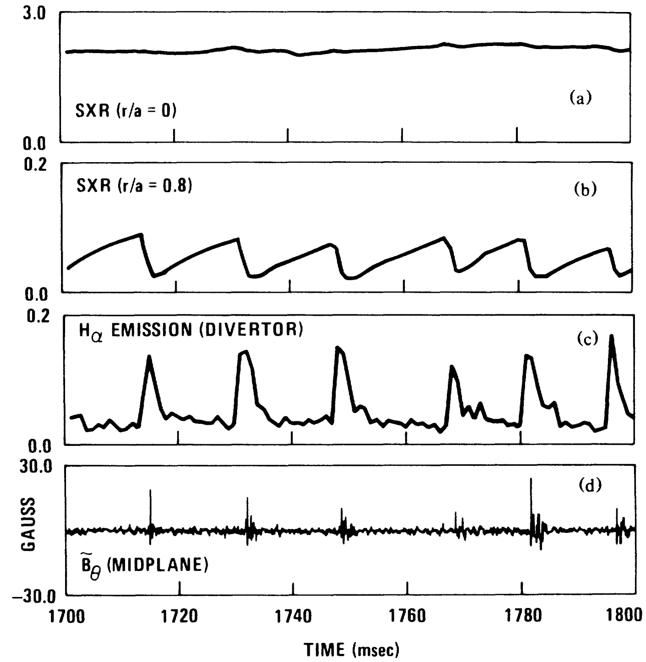

FIG. 3. Time expansion of traces for (a) central soft-x-ray emission; (b) soft-x-ray emission at 0.8 of the minor radius; (c) H_α emission from the divertor region; (d) amplitude of poloidal-field fluctuations at the outer-wall midplane (in gauss).

wall of the DIII-D vacuum vessel. Shown is the flux-surface equilibrium, radial current density, and q profiles at two times: (a) before beam injection and (b) in steady state when $\beta_p = 3.5$. The radial current profile ex-

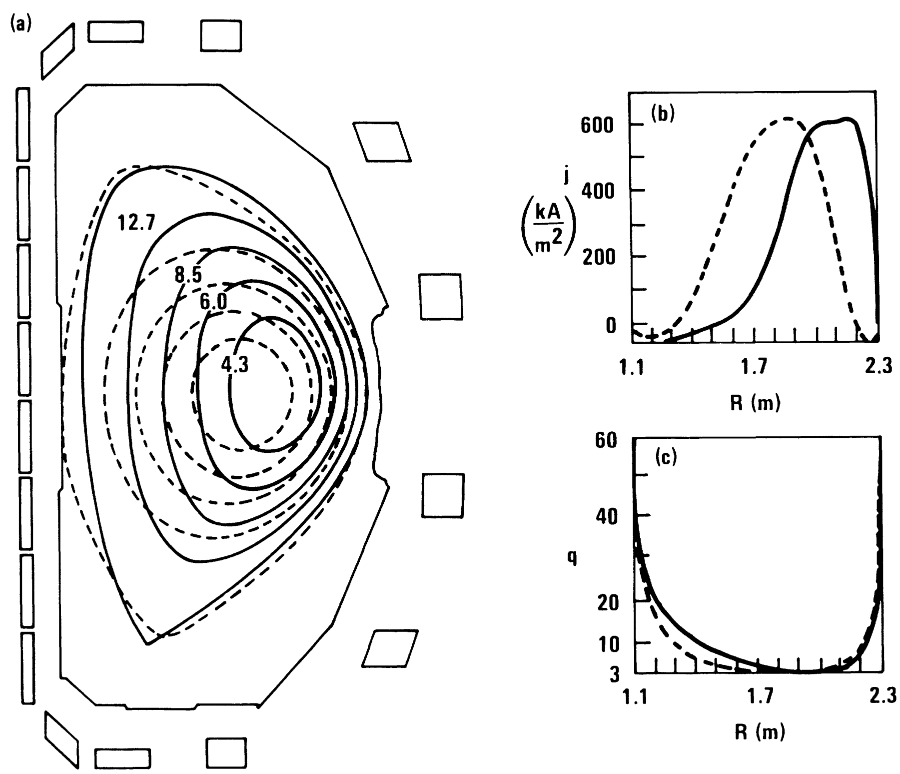

FIG. 4. A comparison between Ohmic (1.03 s, dashed line) and beam-driven (1.4 s, solid line) EFITD magnetic analysis of (a) flux surfaces, (b) midplane plasma current density, and (c) safety factor q. This analysis is based on a third-degree polynomial in magnetic flux.

hibits [see Fig. 4(b)] a 0.2 m outward Shafranov shift and an extreme outward peaking which, together with $\epsilon\beta_p > 1$, are indicators of possible second-region stability.[16-21] Several methods have been proposed to enter the second stability region. These include operation with indented bean-shaped cross sections[22,23] high safety factor,[24,25] large aspect ratio,[26] and small aspect ratio with high safety factor and high shear.[27] Our experiments are of the latter type.

The issue of whether these plasmas entered the second stable regime revolves around the exact value of the axial safety factor q_0. MHD equilibrium analysis of external magnetic measurements can determine accurately the edge q (or q at the 95% flux surface, q_{95}), the magnetic axis shift, the poloidal beta β_p, the plasma internal inductance l_i,[15] and the plasma shape. Information on q_0 is only weakly obtained and is dependent on the functional forms assumed in the fitting of the current profile. Our best estimates are that the axial q_0 during neutral-beam-injection current drive is about 3. The absence of soft-x-ray sawteeth supports $q_0 > 1$ in the Ohmically heated plasma, and the drop in l_i seen in Fig. 1(g) shows current-profile broadening during neutral-beam injection that would further increase q_0. Ballooning-mode[28] analysis indicates that the plasma is entering the second stability region if $q_0 > 2.5$.

Needed are more definitive experiments, with current-profile measurements, operating at toroidal β's that substantially exceed first-stability boundaries. Such experiments will help determine whether the predicted practical advantages of the second stability region, such as lower magnetic field or high-temperature advanced fuel tokamak reactors, can be realized.

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