Stationary, High Bootstrap Fraction Plasmas in DIII-D Without Inductive Current Control*

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Operation at high β_N and β_p without current drive by transformer induction is a necessary characteristic of steady-state tokamak reactors. At high bootstrap fraction (f_{bs}) the pressure and current profiles are constrained to be consistent, reducing the possibility of external optimization and raising questions of current and pressure control, as well as of stability limits. To begin addressing these questions, DIII-D experiments with stationary plasmas but without transformer induction or current regulation have reached $\beta_N \approx \beta_p \approx 3.0$ with $f_{bs} > 75\%$. These conditions have been maintained for >2.2 seconds, in plasmas with $I_p \approx 0.65$ MA and $\beta \approx 1.5\%$. The plasmas show intermittent ITB formation in all channels (n_e, T_e, T_i, Ω). The improved confinement and higher β associated with the ITBs leads to current overdrive (>50 kA/s). The amplitude of the current and pressure variations increases as β is raised. The rms current and total energy variations are 1.3% and 6% respectively for the example in Fig. 1. The self-consistent plasma state has a broad current profile, with low internal inductance ($\ell_i \leq 0.6$), no-wall n=1 ideal kink β limit at $\sim 4\ell_i$, and weakly inverted q (e.g., $q_0 \approx 2.4$, $q_{min} \approx 2.1$). Typically, there is 65%–80% bootstrap current, 20%–30% NBCD, and 0%–5% ECCD. While there have been a number of studies of tokamak plasmas without transformer induction but far from β limits [1–4], and of essentially 100% noninductive plasmas at higher β but with transformer current control [5,6], this is the first study to explore plasma behavior near β limits without transformer control or current regulation.

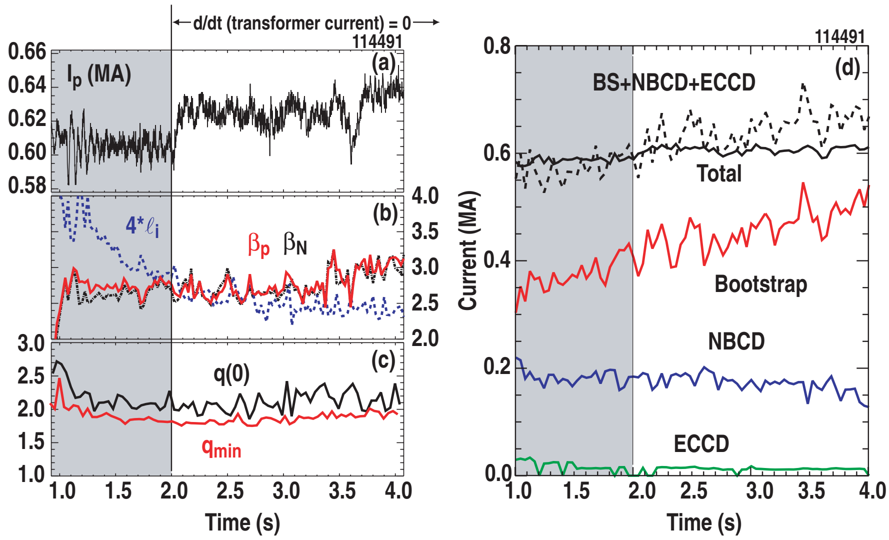

Fig. 1. Parameters for a 2 s, fully noninductive, stationary plasma (114491). The transformer current is held fixed (clamped) after 2.0 s. (a) Plasma current, (b) β_p (solid red), β_N (dot-dash black), and $4*\ell_i$ (dash blue), (c) q_0 and q_{min}, and (d) calculated bootstrap current, NBCD, ECCD, and a comparison of the total of these with the measured current. Note the expanded vertical scales.

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Efficient operation of a steady-state tokamak reactor requires very high f_{bs}, ~1.0±0.1, indicating very close coupling between J(r) and p(r). We need to know what the self-consistent profiles are, what are the β limits under these conditions, and whether β is sufficient for reactor operation. Also, are these states are unique, are they stable against transient fluctuations, and can control methods be devised to maintain optimum conditions?

Figure 1 illustrates the behavior without transformer control of the current. After the transformer current is clamped, there is a brief transient jump (~20 kA) associated with changing the control algorithm, thereafter I_p is maintained noninductively. In this example, I_p shows fairly rapid variations, up to 6% in ~0.1 s. The toroidal voltage is near zero, but has very large fluctuations; V(ρ=1) = 6±21 mV, for $2 \le t \le 4$ s with a 280 ms average. The stored energy continues to rise through this period, indicating gradual improvement in confinement. In the absence of ITB behavior, $H_{89P} \approx 2.0–2.2$. There is a slight broadening of the current profile indicated by the slow decrease in ℓ_i and the increase in q_0 and q_{min}. The bootstrap current is steadily rising, reaching 80% of the sum of the calculated currents. All three components (bootstrap, NBCD, and ECCD) are calculated from the measured density and temperature profiles, and the q profiles as determined from equilibrium analysis (including internal MSE data). The fact that the sum of the calculated currents exceeds the measured current is not necessarily an indication of overdrive. It more likely indicates the accuracy of the models used in determining profiles and in calculating the currents. Current and energy fluctuations of the magnitude seen here may not be acceptable in a burning plasma. In steady-state reactors, the transformer may have to be used to limit excursions of the total current.

In spite of current and pressure fluctuations, the plasma tends to maintain its average parameters, a positive result providing evidence of dynamical stability. Figure 2 shows a transient event associated with formation of an ITB. The transformer is clamped at 3.0 s. For ~0.7 s the stored energy rises, and the power injected falls, indicating confinement improvement; H_{89P} goes from 2.0 to 3.0. The event ends with a burst of *m/n=3/1* MHD activity. The profiles before and after the event are almost identical, but at the peak of the stored energy there is a definite ITB in all parameters at ρ ≈ 0.7. Steepening of the gradients in this region leads to a large increase in J_{bs} at $0.5 \le \rho \le 0.8$, and to the transient increase in I_p.

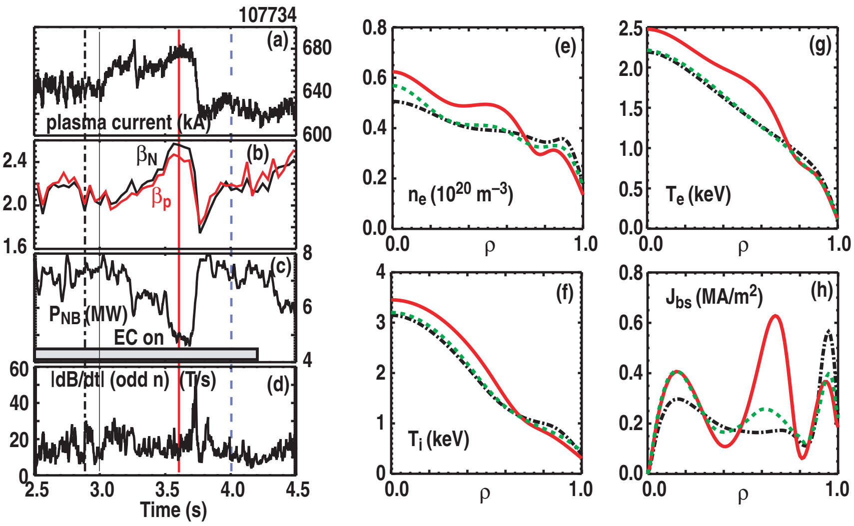

Fig. 2. A transient event associated with an ITB. (a) Plasma current (the transformer is clamped at 3.0 s), (b) β_N and β_p, (c) P_{NB} (the bar indicates the duration of ECH), (d) Mirnov amplitude for odd toroidal modes, (e–h) n_e, T_i, T_e, and J_{bs} profiles before (2.885 s; black dash-dot), during (3.605 s; red solid), and after (4.005 s; green dash) the ITB event.

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