GA–A24342

TRANSFORMERLESS OPERATION OF DIII–D WITH HIGH BOOTSTRAP FRACTION

by
P.A. POLITZER, A.W. HYATT, T.C. LUCE, M.A. MAHDAVI, M. MURAKAMI, F.W. PERKINS, R. PRATER, A.D. TURNBULL, T.A. CASPER, J.R. FERRON, R.J. JAYAKUMAR, R.J. LA HAYE, E.A. LAZARUS, C.C. PETTY, and M.R. WADE

JULY 2003

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

GA–A24342

TRANSFORMERLESS OPERATION OF DIII–D WITH HIGH BOOTSTRAP FRACTION

by

P.A. POLITZER, A.W. HYATT, T.C. LUCE, M.A. MAHDAVI, M. MURAKAMI,* F.W. PERKINS,† R. PRATER, A.D. TURNBULL, T.A. CASPER,‡ J.R. FERRON, R.J. JAYAKUMAR,‡ R.J. LA HAYE, E.A. LAZARUS,* C.C. PETTY, and M.R. WADE*

This is a preprint of a paper to be presented at the 30th European Physical Society Conference on Controlled Fusion and Plasma Physics, St Petersburg, Russia, July 7–11, 2003 and to be published in the *Proceedings.*

*Oak Ridge National Laboratory, Oak Ridge, Tennessee.

†Princeton Plasma Physics Laboratory, Princeton, New Jersey.

‡Lawrence Livermore Natonal Laboratory, Livermore, California.

Work supported by
the U.S. Department of Energy
under Contract Nos. DE-AC03-99ER54463, DE-AC05-00OR22725,
DE-AC02-76CH03073, and W-7405-ENG-48

GENERAL ATOMICS PROJECT 30033
JULY 2003

Transformerless Operation of DIII-D with High Bootstrap Fraction

P.A. Politzer,[1] A.W. Hyatt,[1] T.C. Luce,[1] M.A. Mahdavi,[1] M. Murakami,[2] F.W. Perkins,[3] R. Prater,[1] A.D. Turnbull,[1] T.A. Casper,[4] J.R. Ferron,[1] R.J. Jayakumar,[4] R.J. LaHaye,[1] E.A. Lazarus,[2] C.C. Petty,[1] and M.R. Wade[2]

[1]*General Atomics, P.O. Box 85608, San Diego, California, 92186 USA*

[2]*Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee, 37831 USA*

[3]*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey, 08543 USA*

[4]*Lawrence Livermore National Laboratory,* P.O. Box 808, *Livermore, California, 94551 USA*

We have initiated an experimental program to address some of the questions associated with operation of a tokamak with high bootstrap current fraction under high performance conditions, without assistance from a transformer. In these discharges we have maintained stationary (or slowly improving) conditions for >2.2 s at $\beta_N \approx \beta_p \approx 2.8$ (Fig. 1). Significant current overdrive, with dI/dt > 50 kA/s and zero or negative voltage, is sustained for over 0.7 s. The overdrive condition is usually ended with the appearance of MHD activity, which alters the profiles and reduces the bootstrap current. Characteristically these plasmas have 65%–80% bootstrap current, 25%–30% NBCD, and 5%–10% ECCD.

Fully noninductive operation is essential for steady-state tokamaks. For efficient operation, the bootstrap current fraction must be close to 100%, allowing for a small additional (~10%) external current drive capability to be used for control. In such plasmas the current and pressure profiles are tightly coupled because J(r) is entirely determined by p(r) (or more accurately by the kinetic profiles). The pressure gradient in turn is determined by transport coefficients which depend on the poloidal field profile [1–3].

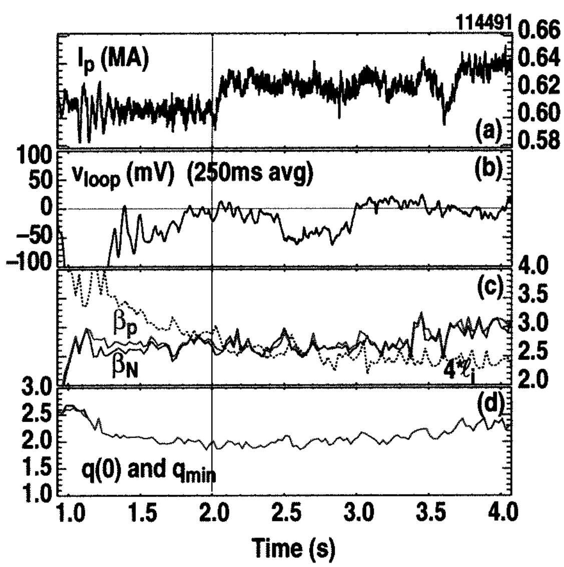

Fig. 1. Parameters for a 2 s, fully noninductive, stationary plasma (114491). The transformer current is held fixed after 2.0 s. (a) Plasma current, (b) loop voltage (0.25 s average), (c) β_p (solid red), β_N (dot-dash black), and $4*\ell_i$ (dash blue), (d) $q(0)$ (there is no q profile inversion).

There are several important questions: what are the self-consistent profiles of pressure and current; what are the beta limits under these conditions and is beta sufficient for reactor operation; are these states unique; are these states stable against transient fluctuations; can control methods be devised to maintain optimum conditions? In the experiments reported here we begin to address these issues. These results illustrate the need for development of new control techniques for noninductive, high bootstrap fraction operation of large burning plasmas.

These discharges are prepared using the transformer, NBI, and ECH to approximate the expected noninductive profiles. Then, to allow the plasma to relax noninductively, the transformer current is held constant or else a novel voltage feedback technique is used to maintain zero voltage at the plasma surface. The NB power is controlled so as to maintain a constant diamagnetic signal. A typical plasma is a high triangularity, symmetric double-null shape,operating in ELMy H–mode, with an initial 650 kA plasma current, and 5–8 MW of auxiliary heating (Fig. 2). In this discharge, the transformer current is held fixed from 2.0 s onward. Typically, $q_{95} \sim 10$ and $\beta \sim 1.5\%$.

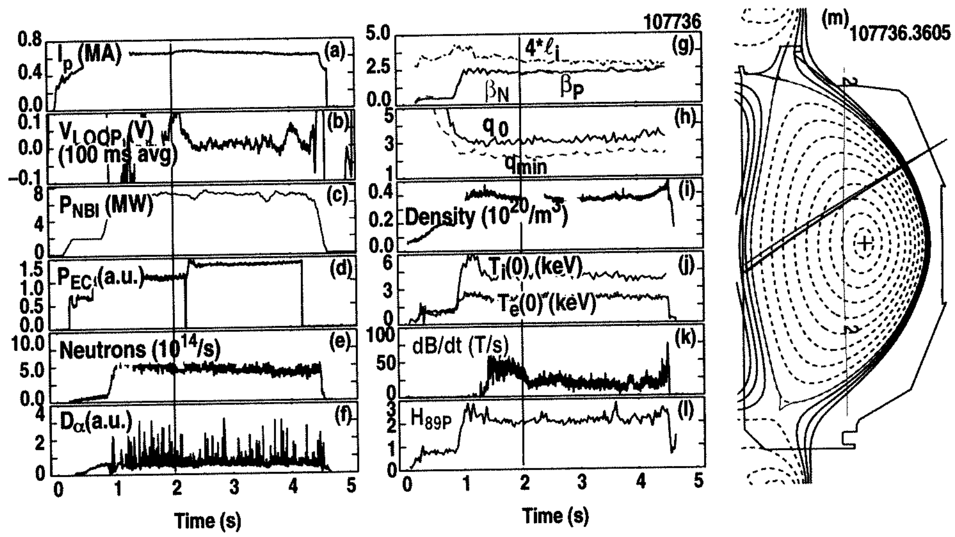

Fig. 2. Parameters of DIII-D discharge 107736. The transformer current is clamped at 2.0 s. (a) current, (b) voltage (100 ms smooth), (c) NB power, (d) EC power, (e) neutron rate, (f) D_α at divertor, (g) β_N, β_P, and $4*\ell_i$, (h) q_0 and q_{min}, (i) density, (j) T_i and T_e, (k) Mirnov amplitude, (l) H_{89P}, (m) plasma shape at 3.605 s, showing EC rays and 2nd harmonic resonance location.

Note that, although most parameters seem to be constant on the scale of the shot duration, there is a slow evolution of the current and pressure profiles, on roughly a 20 s time scale (Table I). The lowest mode time constant for evolution of the total current at constant voltage is about 2.7 s. If this is the correct time scale for evolution, and the evolution is a simple exponential, a projection can be made for the final values using $x(\infty) = x(0)+2.7*(dx/dt)(0)$. Of course, this neglects evolution of the kinetic profiles, but it does indicate that the conditions achieved are close to the anticipated final stationary state.

The n_e, T_e, T_i, and Ω (toroidal rotation) profiles show no evolution during the noninductive phase. The current density peak near $r/a \approx 0.25$ drops somewhat, corresponding to the increase in q_{min} and the drop in ℓ_i. There is a brief excursion between 3.48 and 3.62 s, showing an improvement in confinement, reduction in input power, and changes in the T_e, Ω, and J_{bs} profiles. During this

Table I. Values of indicated parameters at 3.0 s in 107736; approximate rate of change; inferred time constant; projected final value based on 2.7 s time constant.

	x	dx/dt	x/(dx/dt) (s)	est. x(∞)
I_p (MA)	0.64	–0.030	21	0.56
ℓ_i	0.75	–0.025	30	0.68
q_0	3.2	+0.04	80	3.3
q_{min}	2.3	+0.2	12	2.8
β_p	2.3	+0.12	19	2.6
W (MJ)	0.54	–0.02	27	0.49

transient, the total current increases at ~130 kA/s. As indicated in Fig. 3, the bootstrap fraction averages ~70% during the NI phase, NBCD is constant at about 20%, ECCD is ~4%, and the remainder, presumably Ohmic current is ~6%. The contributions to the bootstrap current from n_e, T_e, and T_i gradient terms are in the ratios 37:36:28. The bootstrap alignment parameter reaches BSA = 0.71; this is a measure of the rf power needed to drive the difference between the bootstrap and total currents, defined as

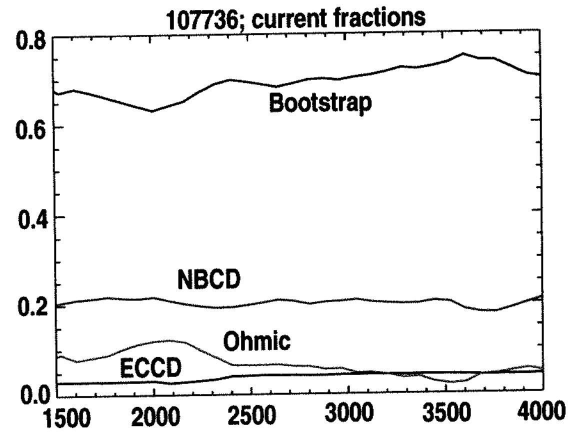

Fig. 3. Fractional contributions to total current for discharge 107736 (500 ms avg).

$$BSA = 1 - \left[\int d\rho \frac{\rho F}{\langle B_\varphi^2 \rangle} \frac{n_e}{T_e} \left| J_{||} - J_{boot} \right| \Big/ \int d\rho \frac{\rho F}{\langle B_\varphi^2 \rangle} \frac{n_e}{T_e} \left| J_{||} \right| \right] . \qquad (1)$$

In order to assess the dependence of the final, noninductive state on the initial conditions, a density scan and a timing scan were carried out. The three discharges illustrated in Fig. 4 were prepared identically except for varying initial density. After freezing the transformer current at 2.0 s, the density and current evolve without control. As indicated the line-averaged electron density, the total current, and the bootstrap current fraction are closely coupled. Increasing the density leads to a much higher bootstrap fraction and to a reduction in the current decay rate. Even small variations in the density and current are correlated. There is an increase in bootstrap fraction whenever the density rises or remains constant for an interval.

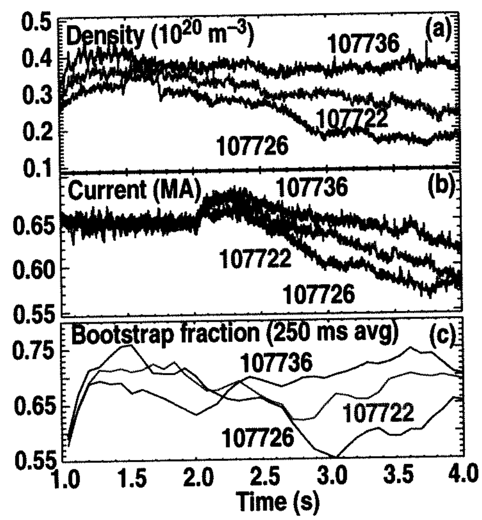

Fig. 4. Three discharges prepared with different initial densities. The transformer current is fixed at 2.0 s. (a) line-average density (CO_2 interferometer); (b) total current; (c) bootstrap current fraction. The jump in total current from 2.0 to 2.3 s is due to a voltage transient associated with the transformer current clamping.

In the timing scan we look at three identically prepared discharges. The switch from controlled to uncontrolled plasma current is made at 1.0, 2.0, and 3.0 s. As shown in Fig. 5, the current profile broadens during the driven phase, as indicated by the falling internal inductance, but broadens much more slowly after the transformer current is fixed. Also shown in Fig. 5 is the time dependence of the plasma current. Starting with a high internal inductance appears to lead to a more rapid decay of the plasma current. As indicated above, the preferred noninductive state has a low inductance and a broad current profile. The differences among the density or temperature profiles are not large enough to be significant, given uncertainties in measurement.

During these high β_p and β_N discharges, ITB-like behavior is seen, particularly in the density, electron temperature, and rotation profiles. Associated with the period of improved confinement is a decrease in the power required to maintain the pressure, and an increase in the total current. An outstanding example of this behavior is illustrated in Fig. 6. This condition is terminated by a short burst of *m=3/n=1* MHD activity. After recovery the total thermal energy exceeds its earlier value but the current is 8% lower. During the ITB, the n_e and T_e gradients near ρ = 0.7 increase, giving a large local increase in the bootstrap current density. Curiously, the rotation is slowed in the outer part of the plasma.

Work supported by U.S. Department of Energy under Contracts DE-AC03-99ER54463, DE-AC05-00OR22725, DE-AC02-76CH03073, and W-7405-ENG-48.

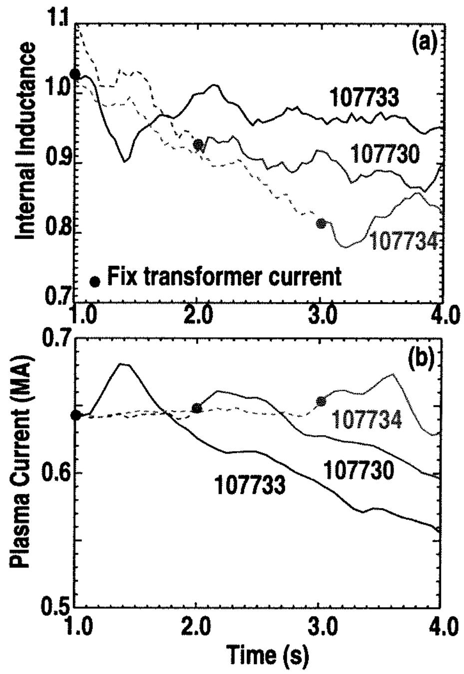

Fig. 5. (a) Internal inductance and (b) total plasma current. The dashed line indicates the time under transformer control. The transformer current is fixed at the time indicated by the dot.

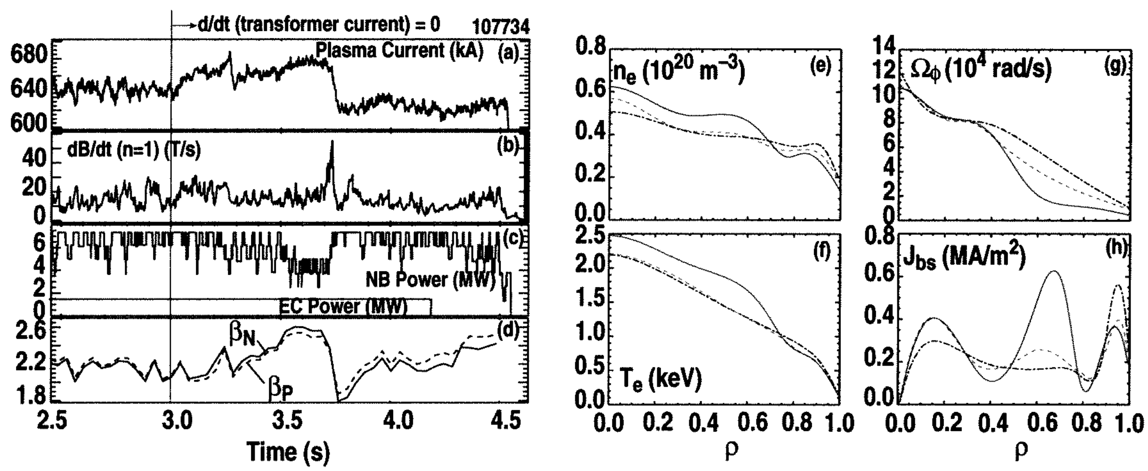

Fig. 6. An ITB leads to increasing current for > 0.5 s. (a) Plasma current. The transformer current is fixed from 3.0 s onward. (b) Odd toroidal mode number component of the Mirnov signal. (c) NB and EC power levels. (d) β_N and β_p. (e, f, g, h) density, T_e, rotation, and bootstrap current profiles before (2.885 s; black dash-dot), during (3.605 s; red solid), and after (4.005 s; green dash) the ITB.

[1] Sauter, O., et al., Phys. Rev. Lett. **84**, 3322 (2000); Sauter, O., et al., Phys. Plasmas **8**, 2199 (2001); Henderson, M.A., et al., Phys. Plasmas **10**, 1796 (2003).
[2] Oikawa, T., et al., Nucl. Fusion **40**, 435 (2000); Kamada, Y., et al., Nucl. Fusion **41**, 1311 (2001); Fujita, T., et al., Phys. Rev. Lett. **87**, 085001 (2001); Ide, S., et al., Plasma Phys. Control. Fusion **44**, L63 (2002).
[3] Wolf, R.C., et al., Nucl. Fusion **41**, 1259 (2001).