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Evolution of high β_p plasmas with improved stability and confinement*

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Experiments to explore the long-time evolution of noninductive, high β_p plasmas in the DIII-D tokamak [*Plasma Physics and Controlled Nuclear Fusion Research, 1986* (International Atomic Energy Agency, Vienna, 1987), Vol. 1, p. 159], have identified a new, quiescent, high performance regime. The experiments were carried out at low current (400–800 kA) with medium power neutral beam injection (3–10 MW). This regime is characterized by high q_0 (> 2) and moderate I_i (~ 1.3). It is reached by slow relaxation of the current profile, on the resistive time scale. As the profiles relax, q_0 rises and I_i falls. When q_0 goes above 2 (approximately), magnetohydrodynamic (MHD) activity disappears, and the stored energy rises. Most dramatic is the strong peaking of the central density, which increases by as much as a factor of 2. The improved central confinement appears similar to the PEP/reversed central shear/second stable core modes seen in tokamak experiments, but in this case without external intervention or transient excitation. At high current, a similar, but slower relaxation is seen. Also notable in connection with these discharges is the behavior of the edge and scrape-off layer (SOL). The edge localized modes (ELM's) as seen previously, are small and very rapid (to 1 kHz). The SOL exhibits high density ($> 1 \times 10^{19} \text{ m}^{-3}$), which shows little or no falloff with radius. Also the power deposition at the divertor surface is very broad, up to four times the width usually seen. This regime is of particular interest for the development of steady-state tokamak operating scenarios, for the Tokamak Physics Experiment (TPX), and following reactors.

I. INTRODUCTION

The goal of the “advanced tokamak” program is the improvement of tokamak performance (stability, confinement, current drive efficiency) using advanced plasma

shape and profile control techniques to maintain a tokamak discharge in otherwise inaccessible regions of parameter space. One of several configurations being explored is the high poloidal beta (β_p) regime ($\epsilon\beta_p > 1$).¹ Operation in this regime is of interest because of the large bootstrap current at high β_p , which reduces the requirement for external noninductive current drive, as well as the prospect

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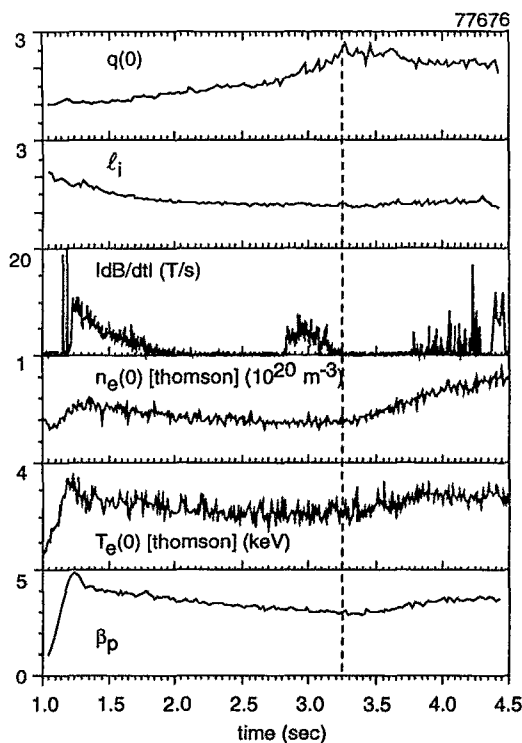


FIG. 1. Time histories of q_0 , l_i , Mirnov fluctuation amplitude, central n_e and T_e (from Thomson scattering), and β_p . The vertical line marks the transition between the resistive relaxation phase and the improved core confinement phase. NBI starts at $t = 1.0$ s.

for removal of ballooning mode stability limits which may lead to improved confinement, increased pressure, and operation at lower plasma current.² Initial studies of low-current, moderate-to-high-power (neutral beam heated) plasmas have been undertaken with the DIII-D tokamak³ in order to explore the characteristics of this regime.

In this paper we report observations of the evolution of the plasma equilibrium, stability, and transport in the high β_p regime in the DIII-D tokamak. With the resistive evolution of the current profile, we have observed a transition to a regime with improved confinement in the core of the discharge (particularly particle confinement) leading to a peaking of the density profile with a doubling of the density at the axis. Associated with the density peaking is an increase in the bootstrap current fraction to about 80%.

The transition to this regime is associated with an increase in the value of the axis safety factor to $q_0 \geq 2$. After the transition the density on axis rises, doubling in about 1 s. In this regime, experimental observations and theory indicate that the plasma is stable to both low n kink and ballooning magnetohydrodynamic (MHD) modes. The global energy confinement, initially at a typical high confinement (H-mode) level, improves as the density peaks (by over 30%). This regime is similar in many respects to the peaked pressure modes seen in other tokamak experiments (e.g., the PEP mode in the Joint European Torus (JET), or the LHEP mode in Tore Supra).⁴ However in the present case no external trigger is used, rather the cur-

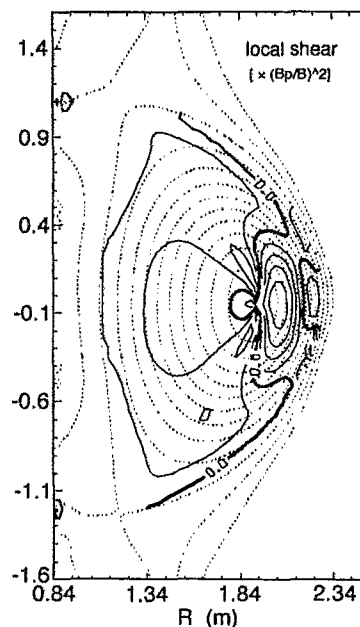


FIG. 2. Flux surfaces (dotted lines) and contours of local shear [scaled by $(B_p/B)^2$ to remove the singularity at the X points] for discharge 77676 at 4.36 s.

rent profile relaxes on a resistive time scale to the requisite configuration. These discharges show other interesting features, particularly in the properties of the scrape-off layer (SOL). The outer half of the plasma has the characteristics of an ELMy H mode. However, the SOL is very broad, as is the power deposition profile at the strike points.

In summary, these discharges indicate the presence of a plasma regime showing good prospects for advanced tokamak operation. The critical element in extending and improving this behavior is the development of real-time control of the current profile in order to maintain the optimal characteristics. In Sec. II, we characterize the evolution of the equilibrium for a discharge entering the improved core confinement regime; the observations of fluctuations are presented in Sec. III, along with numerical analyses of the stability of the equilibria; the improvements in particle and energy confinement are documented in Sec. IV; and the behavior of the SOL plasma is discussed in Sec. V.

II. EQUILIBRIA

A. Basic discharge characteristics

The high β_p , high bootstrap fraction plasmas have a high triangularity, double-null separatrix shape. The toroidal magnetic field is 1.9–2.1 T, and the plasma current is 400–800 kA. Heating is with 3–10 MW of neutral beam injection (NBI). The lower limit of 400 kA is set by the increasing difficulty of confining fast ions as the current is reduced. As discussed in a later section, at 400 kA there is a large (up to 50%) prompt loss of fast ions from the plasma.

The temporal evolution of a typical low-current discharge proceeds through several well-defined stages. Ini-

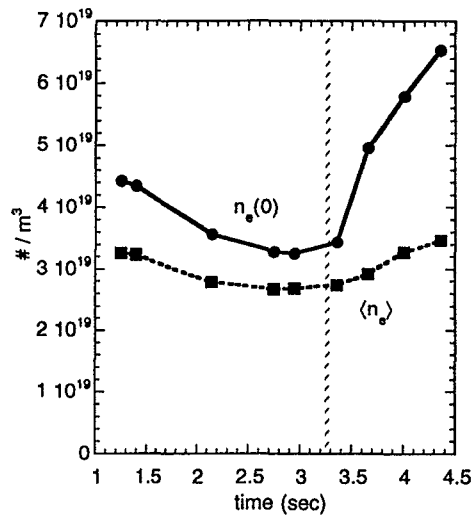


FIG. 3. Electron density at the plasma axis, and average density versus time. Note the approximately linear rise in $n_e(0)$ after 3.3 s.

tially, we allow up to 1 s for the establishment and relaxation of the Ohmic target plasma. With initiation of NBI, a transient very high β_p configuration is established, with a large fast ion population (30%–40%) and strong MHD activity. On a resistive time scale, the current profile broadens from the Ohmic shape ($q_0 \approx 1$; $l_i \approx 1.8$) toward a profile characteristic of a combination of neutral beam current drive (NBCD) and bootstrap current ($q_0 \gtrsim 2$; $l_i \approx 1.2$). During this evolution the MHD activity initially disappears, but is seen again when q_0 is in the neighborhood of 2. Following the disappearance of the $q=2$ surface and the MHD activity, the central electron density rises, doubling in about 1 s. While the central density rises, the density profile in the outer half of the plasma changes very little from the characteristic ELMing H-mode shape seen earlier in the discharge.

The most interesting behavior occurs for the 400 kA discharges. At higher current similar behavior is seen, but on a slower time scale because of the higher electron temperature; consequently there is not enough time to observe the behavior after the transition to $q_0 > 2$. The time history of a 400 kA DIII-D discharge (77676) is shown in Fig. 1. The equilibrium at 4.36 s is shown in Fig. 2. Note that, because of the high β_p (≈ 3.6) and peaked pressure ($p_0/\langle p \rangle \approx 8$), there is a large outward shift of the magnetic axis. Note also the region of reversal in the local magnetic shear at the outer midplane.

The profile analyses of discharge 77676 presented in this paper were obtained by reconstruction of the equilibrium configuration at nine times during the discharge (as indicated in Figs. 3, 5, 6, and 7). The reconstruction process includes data on n_e and T_e from the multipulse Thomson scattering system, n_e data from the CO₂ laser interferometers, T_e data from the HECE system, T_i and toroidal rotation data from the CER system, visible bremsstrahlung measurements, and radiated power as measured by the bolometer arrays. This information is combined with the full DIII-D complement of magnetic diagnostics, including the 8-channel motional Stark effect (MSE) measurement, to construct a consistent magnetic equilibrium and spatial profiles using the EFIT⁵ and ENERGY⁶ codes. The fast ion deposition and distribution, as well as the individual components of the plasma current (NBCD, bootstrap, inductive) are calculated using the ONETWO⁷ code, and are consistently incorporated into the reconstruction (see Sec. IV A for further discussion).

An ancillary benefit of high β_p operation is the improvement in diagnostic capability resulting from the large outward shift of the magnetic axis (to the range 1.86–1.94 m). This allows the use of Thomson scattering data ($R_{\text{Thomson}} = 1.94$ m) to determine profiles very close to the axis (in the range $\rho \leq 0.05$). Also, four of the MSE measurements are inboard of the axis, which leads to excellent

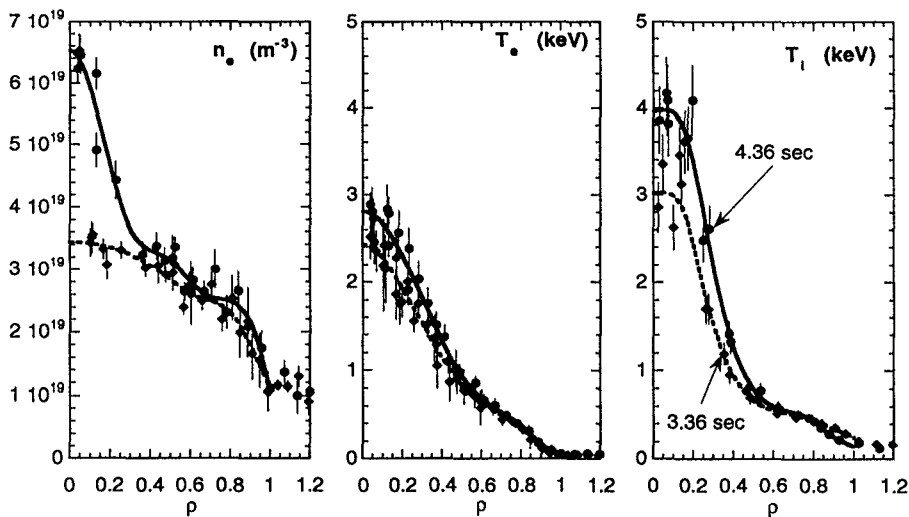


FIG. 4. Electron density, electron temperature (both from Thomson scattering), and ion temperature (from CER measurement) profiles for discharge 77676 at 3.36 and 4.36 s. The confinement improvement is inside $\rho \approx 0.4$ –0.6.

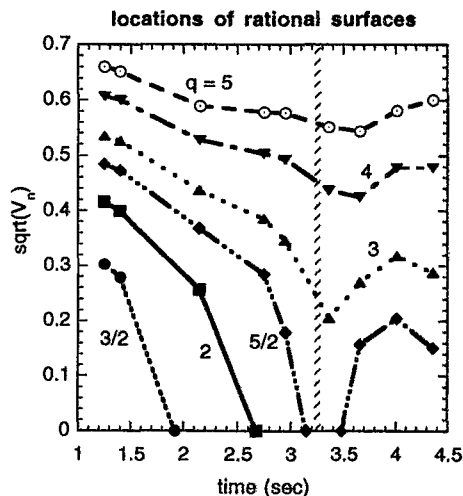


FIG. 5. Locations of low-order rational surfaces as a function of time.

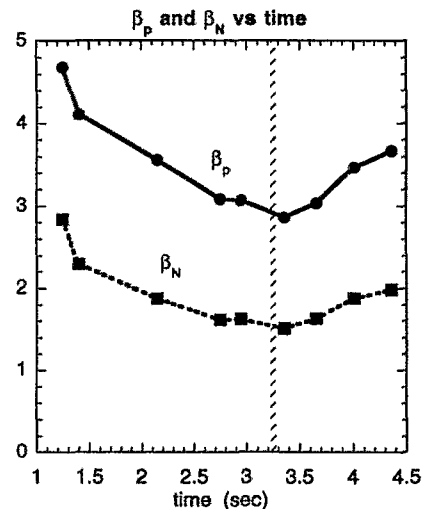


FIG. 6. β_p and $\beta_N [\equiv \beta/(I/aB)]$ versus time.

spatial resolution because of the expansion of the poloidal flux in this region. The radial extent of the measurement volume for the MSE varies from $\Delta R \approx 0.02$ m at the innermost chord to $\Delta R \approx 0.08$ m at the outermost. This transforms to $\Delta \rho \approx 0.02$ m at the innermost chord ($\rho \approx 0.45$), $\Delta \rho \approx 0.07$ near the axis, and $\Delta \rho \approx 0.22$ at the outermost chord ($\rho \approx 0.68$). The absolute accuracy of the MSE measurement of the magnetic field pitch angle is limited by the calibration accuracy and is about $\pm 0.5^\circ$. The measurement noise (giving the relative error) is about 0.1° . On the basis of these uncertainties, plus the variation of the fit to the other magnetic data and to the kinetic pressure profile the error in determination of q_0 is estimated to be $\delta(q_0) \leq 0.2$.

B. High-pressure core

The strongest evidence for the existence of the improved core confinement regime is the peaking of the density. Figure 3 shows the time dependence of the central and average electron density. The localization to the plasma core is indicated by the profile comparison (3.36 and 4.36 s) shown in Fig. 4. The region of improved confinement corresponds to $\rho \leq 0.4$. There is also an increase in ion and electron temperature. The profiles outside this radius are characteristic of an ELMing H mode, and do not change significantly during the discharge. The toroidal rotation profile is also peaked; the toroidal velocity at the axis is approximately 1.4×10^5 m/s during the first half of the discharge, rising to 2.2×10^5 m/s by 2.95 s and remaining constant thereafter (corresponding to $\Omega_\phi R/v_{ti} \approx 0.38$).

C. Current profile and the bootstrap current

The evolution of the current profile through this discharge controls the changes in stability and confinement. Figure 5 shows the locations of the low-order rational surfaces as a function of time. During the relaxation phase, the $q=3/2$, 2, and $5/2$ surfaces successively disappear. After the improvement of core confinement, the current peaks again, and q_0 falls.

At the transition, the bootstrap current begins to increase as a result of the increasing β_p (Fig. 6) and density gradient in the core. Prior to the transition, the fractions of the total current due to bootstrap, NBCD, and Ohmic current are approximately 40%, 26%, and 34%, respectively (see Fig. 7). At 4.36 s, the bootstrap current is 78% of the total, the NBCD is 23%, and the total Ohmic current fraction is -1% . This meets the advanced tokamak goal of providing most of the plasma current via the bootstrap effect.

However, as seen in the profiles (Fig. 8), the bootstrap current is rising fast enough to induce a back EMF and a reversed Ohmic current in the region of maximum density gradient (near $\rho=0.2$). The tendency for the bootstrap current to generate a hollow current profile with reversed shear is counteracted by the inductive response of the plasma. The net result is a peaking of the total current near

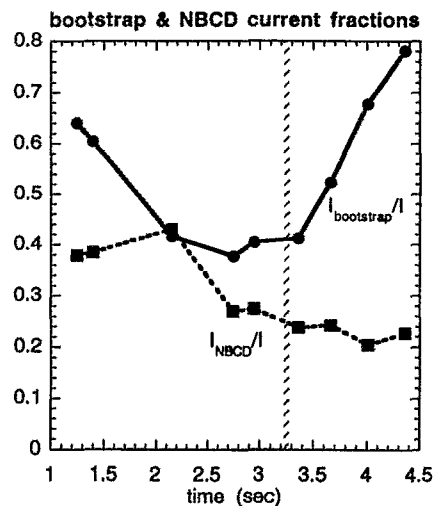


FIG. 7. Fractions of the total current due to the bootstrap current and to neutral-beam-driven current.

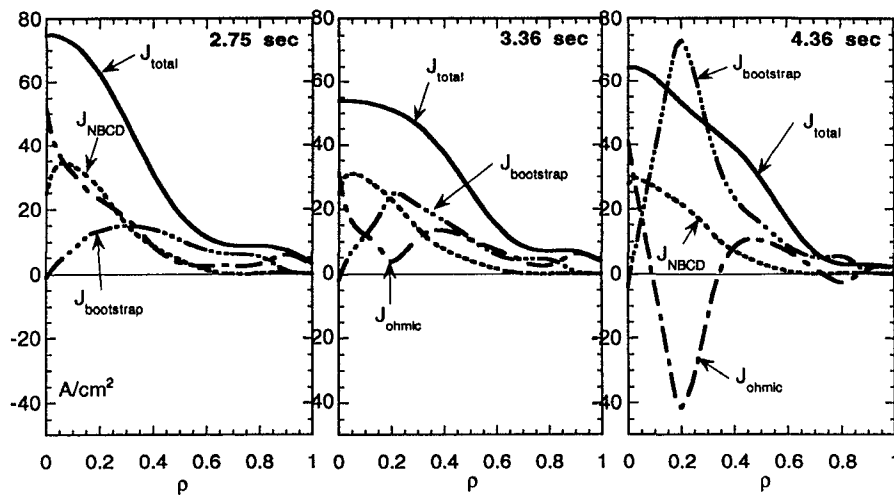


FIG. 8. Profiles of the total current and its individual components (bootstrap, NBCD, and Ohmic) during the relaxation phase, at the transition, and near the end of the discharge.

the axis late in the discharge. In turn, this leads to reduction in q_0 , return of the 3/1 instability, and a decrease in the rate of rise of the density on axis.

III. STABILITY ANALYSIS AND FLUCTUATIONS

A. MHD observations

The spectrum of MHD fluctuations as seen by a magnetic probe are shown in Fig. 9. Initially (at 1.50 s) there is a large amplitude oscillation at about 11 kHz which has not been identified. The amplitude of this mode decreases with time, and at about 1.75 s a shift to a new mode at 15 kHz occurs. The 15 kHz mode is identified as an $m/n = 2/1$ oscillation. Between 1.75 and 2.81 s the amplitude falls steadily (and the frequency rises to 18 kHz as the plasma rotation increases). At 2.81 s, there is an abrupt transition to a 3/1 mode (at 22 kHz), which decreases in

amplitude until it is no longer seen at 3.35 s. The time for transition from $m=2$ to $m=3$ corresponds closely to the disappearance of the $q=2$ surface. The MHD spectrum is very quiet until short bursts of oscillations begin to be seen at 3.775 s. This oscillation continues until the end of the discharge.

B. Soft x-ray observations

Fluctuations in the emission of soft x rays have also been analyzed for the interval 2.65–3.05 s. As shown in Fig. 10, the soft x-ray fluctuations exhibit strong coherence in the plasma core at this time. [Coherence is defined here as the normalized cross power spectrum for two intersecting soft x-ray channels: $C_{ij}(f; t_n) = |\langle S_{ij}(f; t_n) \rangle| / \sqrt{S_{ii}(f; t_n) S_{jj}(f; t_n)}$, where S_{ij} (S_{ii}) is the cross (auto) power spectrum in a time interval around t_n .] Cross cor-

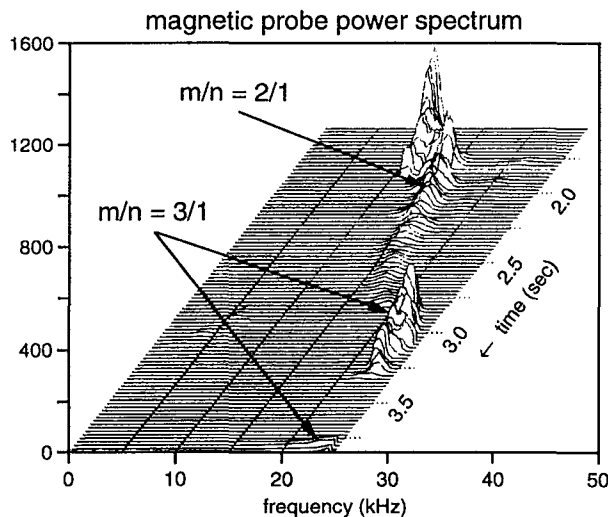


FIG. 9. Spectrum of magnetic fluctuations between 1.50 and 3.90 s. Modes identified as $m/n=2/1$ and 3/1 are labeled.

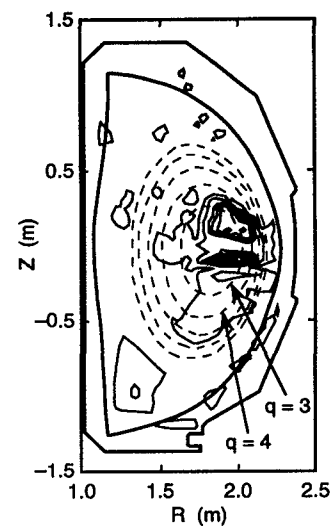


FIG. 10. Coherence of the soft x-ray signals at 3.03 s. The region of maximum coherence is localized around the outboard side of the $q=3$ surface, consistent with the identification of a 3/1 mode. The contours indicate values of 0.2, 0.4, 0.6, 0.7, 0.8, and 0.9.

TABLE I. Stability to ideal $n=1$ modes at selected times.

Time	Stability	Dominant m
1.25	Stable	
1.40	Stable	
2.15	Weakly unstable	2
2.75	Stable	
2.95	Unstable	3
3.36	Stable	
3.66	Weakly unstable	3
4.01	Unstable	3
4.36	Unstable	3

relation between the magnetic and soft x-ray signals also shows a high coherence. These observations confirm that the oscillations seen with external magnetic probes are modes located in the core region. With the exception of the ELM's, there is no other fluctuation seen within the 100 kHz bandwidth of the magnetic diagnostics.

C. Kink analysis

The stability of these equilibria to low n modes has been evaluated using the GATO code.⁸ The results for $n=1$ modes are summarized in Table I.

The calculation of stability at 1.25 and 1.40 s is based on the reconstructed equilibria which have $q_0 \approx 1.1$. Note that the sequence of stable and unstable $m=2$ and 3 modes corresponds closely to the observations. The predicted instabilities are internal modes, with small amplitudes at the plasma surface, and thus are not affected by the location of the conducting wall (assumed to be at the location of the DIII-D wall).

D. Ballooning analysis

The profiles for this discharge have been analyzed for ballooning stability using the MBC code⁹ and the CAMINO

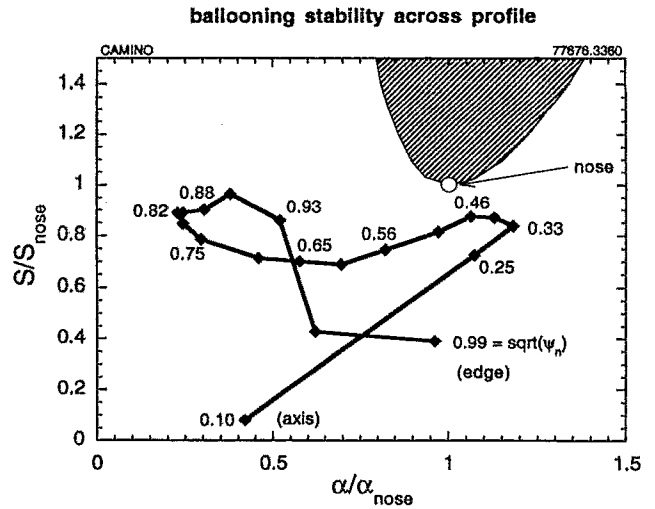


FIG. 12. Normalized S - α plot ($S \propto q', \alpha \propto p'$) for 3.36 s. Each point is normalized to the values of S and α at the "nose" of the instability boundary for that flux surface, and is labeled with the normalized radius. The entire profile is below the first regime p' limit. The region of improved confinement in the core is in the second regime ($0.2 < \rho < 0.5$).

code.¹⁰ The MBC code determines the critical pressure gradient for ballooning mode instability for a given pressure and current profile. The results of this analysis are presented in Fig. 11. Initially, the measured p' ($=dp/d\psi$) is below but close to p'_{crit} over most of the profile. Near the magnetic axis and the plasma surface are regions in which there is no p'_{crit} . As the profile evolves through time, the regions with no p'_{crit} expand until, at the transition to the improved core confinement regime (between 2.95 and 3.36 s) there remains only one surface with a possible pressure gradient limit at $\sqrt{V_n} \approx 0.83$ [Fig. 11(f)]. Subsequently p' in the core increases, while the outer part of the profile maintains a constant shape. More detail is provided

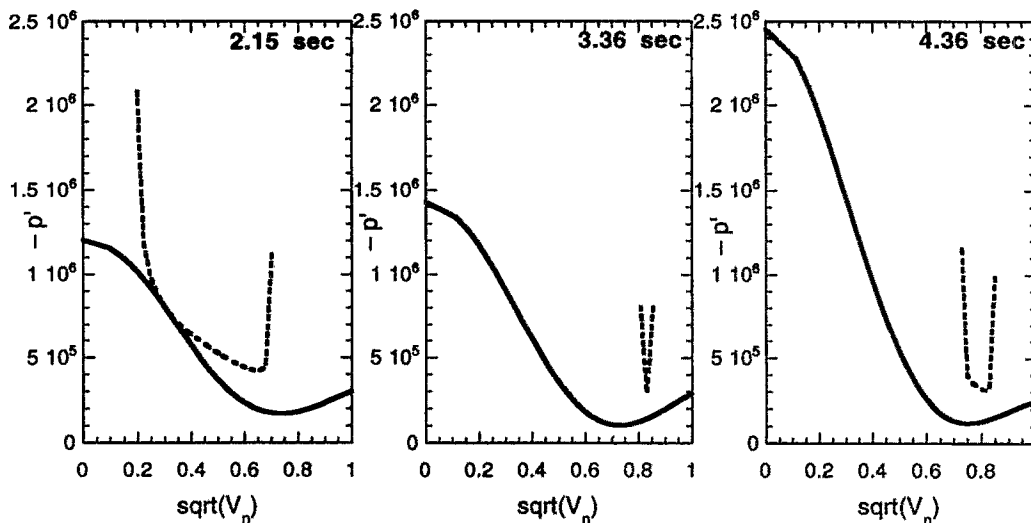


FIG. 11. Profiles of the pressure gradient ($-p'$) and the critical gradient for ballooning stability ($-p'_{crit}$) as a function of time. Note the disappearance of the limit at 3.36 s.

for the 3.66 s time slice using the CAMINO code, which develops a S - α (shear versus pressure gradient) diagram for each flux surface (Fig. 12). For this time, CAMINO finds no surfaces with a first stability limit. Over a small part of the profile, the plasma is close to having a first regime limit to p' . A full error analysis to quantify the uncertainty in the stability analyses presented in Figs. 11 and 12 has not yet been carried out, but it is unlikely to affect the qualitative conclusion that the full plasma profile is below the "nose" of the ballooning mode stability boundary.

IV. CONFINEMENT

A. Fast ion pressure

The reconstruction of the equilibria, and the estimates of the particle and energy confinement time include adjustments for prompt losses of fast ions. Because of the large banana widths of the orbits of fast ions at 400 kA, the confinement of fast ions is very sensitive to the fluctuation level. We find that the stored energy (as determined by the equilibrium reconstruction) and the 2.45 MeV neutron production rate (almost entirely due to beam-target D-D reactions) are significantly lower than would be expected on the basis of the nominal injection power. Test discharges with short pulses from a single NBI source superposed on a steady plasma show that the fraction of fast ions retained in the plasma falls as the neutral injection power increases. In order to account for the loss of fast ions, we adjust the input beam current in the deposition calculations to match the measured neutron flux. Using this procedure, the resulting computed total plasma energy (thermal plus fast ions) agrees well with the equilibrium reconstruction. On this basis, the fraction of the total stored energy associated with fast ions is about 32% during most of the discharge, falling to 22% at 4.01 and 4.36 s when thermal confinement is improved. The calculated fast ion pressure profile is included in the total pressure profile used to reconstruct the equilibria and in the stability calculations.

B. Particle confinement

A key result of this experiment is the improvement in particle confinement in the core of the plasma. The particle confinement time in the core is estimated from the change in the density profile after 3.36 s, when $n_e(0)$ begins to increase. For any flux surface, the rate of change of the total number of particles enclosed is given by $dN/dt = S - Q$, where S is the volume source due to net ionization and Q is the flux (diffusive or convective) across the surface. The particle confinement time is defined by $\tau_p \equiv N/Q = N/(S - dN/dt)$. For the core region of the plasma, we assume that the only source is beam fueling, and that ionization of thermal neutral gas can be neglected. Figure 13 shows the source term due to beam fueling and the rate of rise of the particle number as a function of the normalized radius.

Prior to 3.36 s, the density is changing very slowly and the dN/dt term can be neglected, giving approximately

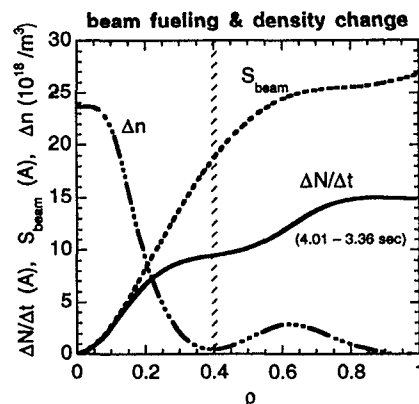


FIG. 13. Beam fueling source (amperes equivalent) and change in the number of particles contained within a flux surface, as a function of normalized radius. The rate of change of the enclosed particle number is determined from the difference in density (plotted as Δn) between 4.01 and 3.36 s.

$\tau_p(t < 3.36) = 1.4$ s at $\rho = 0.4$. Immediately after the transition, the density and source terms have not yet changed, but the dN/dt term must be included, giving $\tau_p(t > 3.36) \approx 2.8$ s at $\rho = 0.4$. On the basis of modeling of the prompt fast ion loss, the estimated uncertainty in the beam fueling source is about 25%. An increase of 25% in S would give $\tau_{\text{before}} \approx 1.1$ s, $\tau_{\text{after}} \approx 1.9$ s, and an improvement factor of 1.7.

C. Energy confinement

There is also a significant improvement in energy confinement accompanying the increase in density in the plasma core. At 4.36 s, the energy confinement time is approximately 2.1 times the ITER-89P L-mode value,¹¹ or 1.6 times the JET/DIII-D value.¹² The increase between 3.36 s and 4.36 s is about a factor of 1.3. Without correction for prompt fast ion losses the increase in normalized confinement is still 30%, but the values are lower ($1.4 \times \tau_{\text{ITER-89P}}$ or $1.1 \times \tau_{\text{JET/DIII-D}}$ at 4.36 s).

V. SOL CHARACTERISTICS AND POWER BALANCE

The n_e , T_e , and T_i profiles in the SOL are very broad. As a result, the heat deposition in the divertor region is not at all localized. This reduces the loading on the material surfaces significantly. The SOL at 3.36 s is analyzed and modeled using the UEDGE code.¹³ Using constant cross-field diffusivities, the best fit to the SOL profiles is found for $D = 1.5$ m²/s, $\chi_e = 1.0$ m²/s, and $\chi_i = 2.5$ m²/s. With these diffusivities, the estimated heat flux across the separatrix is 1.9 MW. The heat flux to the bottom strike point region is measured using the IRTV system (Fig. 14). The peak flux is 0.3 MW/m² and the width at half-peak is about 0.30 m (compared to typical H-mode conditions at similar power with a peak of 1.1 MW/m² and a width of less than 0.1 m).

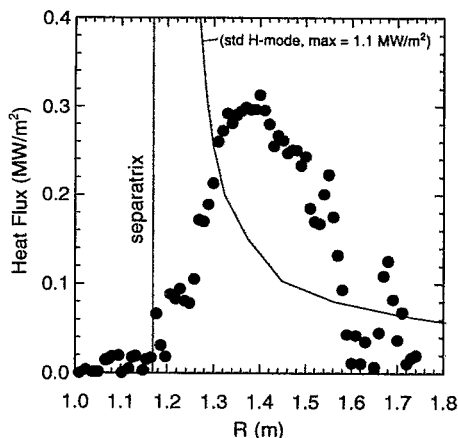


FIG. 14. Heat flux to the lower divertor tiles as a function of major radius. For comparison, the profile of a typical H-mode discharge at the same heating power indicated.

VI. CONCLUSIONS

A. Summary

A low-current, high β_p tokamak discharge is initially prepared with a characteristically Ohmic current profile ($q_0 \sim 1$; high I_i). It evolves through relaxation of the current profile on a resistive time scale to a condition with $q_0 > 2$. In this state, a transition occurs to a regime of greatly improved confinement in the plasma core. The particle confinement time inside $\rho = 0.4$ doubles, and the density profile develops a pronounced peak; $n_e(0)$ doubles in 1 s. The normalized global energy confinement time increases by 30%. As a result of the increase in β_p and the increase in central density gradient, the bootstrap current rises, with $I_{\text{bootstrap}}/I$ reaching 78% (the remainder is contributed by the NBCD). The fraction of the total stored energy associated with fast ions is about 32% during most of the discharge, falling to 22% at 4.01 and 4.36 s when thermal confinement is improved. The calculated fast ion pressure profile is included in the total pressure profile used to reconstruct the equilibria and in the stability calculations.

Associated with these equilibrium changes are significant changes in the observed fluctuation and theoretical stability behavior of the discharge. Observations of MHD and soft x-ray fluctuations, plus the stability analyses provide a consistent picture. Early in the evolution of the discharge, there is a saturated $m/n = 2/1$ instability, which decreases in amplitude as the current profile broadens and q_0 rises. With the disappearance of the $q = 2$ surface, a transition occurs to a saturated $3/1$ mode. These instabilities have strong coherence only in the core of the plasma, near the resonant rational surfaces. With further increase in q_0 , the $3/1$ mode disappears and, in addition, the first regime ballooning limit is removed. At this time the improvement in core particle confinement is seen. Finally, late in the discharge the continued evolution of the current profile due to the increase in the bootstrap current component leads to a reduction in q_0 , and a return of the $3/1$

mode. Neither the soft x rays nor the magnetics show evidence of any other oscillations, up to the 100 kHz limit set by the sampling rate.

B. Principal results

These observations demonstrate the existence of a high β_p , high bootstrap fraction plasma configuration with good confinement which is relevant to advanced tokamak operation. This plasma shows a clear correlation between the absence of MHD activity, the calculation of kink mode stability, the calculation that the plasma core is in the second ballooning stability regime, and the observation of improved confinement in the plasma core. This correlation lends further credibility to the idea of a causal connection between MHD stability and transport.¹⁴ A final observation is that the establishment of an attractive configuration is critically dependent on the details of the current profile. Maintenance of an optimum current profile in a stationary state (as required for steady-state tokamak reactors) requires active external control systems. As seen in these experiments, without external control the plasma does not sustain the optimum profile.

C. Further work

Several questions are raised by this study, and will be the subject of future work. One of the most significant is the establishment of a causal connection (if it exists) between MHD activity and confinement. These experiments strongly suggest such a connection, but they do not distinguish whether stability to both low n and high n modes is necessary or sufficient. A second question is the continued evolution of the current profile. Does the off-axis peaking of the bootstrap current eventually lead to a hollow profile, and can it be sustained? The use of the fast wave and electron cyclotron heating current drive systems being installed on DIII-D will provide needed flexibility in studying this issue.

Applying this improved physics regime to future tokamak reactors will require extending the performance in terms of absolute values of confinement and stability ($n\tau$ and β) as well as normalized values (H and β_N). The normalized values reached here ($H \approx 2.1$, $\beta_N \approx 2.0$) are among the best seen in stationary, ELMing H-mode plasmas, but fall a factor of 2–3 below the values reached in transient states. In order to reach the higher values in steady-state operation, broadening the core region of improved confinement to include a larger fraction of the plasma volume will be required. Allowing (or encouraging) development of an inverted central q profile should also enhance performance. Both relative and absolute performance should also be improved by achieving improved core confinement at higher total plasma current.

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