ATTAINMENT OF QUASI STEADY-STATE H–MODE PLASMAS IN THE DIII–D TOKAMAK

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ABSTRACT

We report the results of experiments on DIII–D where quasi steady-state H–mode plasmas with low amplitude Edge Localized Modes (ELMs) were maintained for 5 seconds. Within one second from the onset of the H–mode, most plasma parameters reach their asymptotic values ($\bar{n}_e \approx 7 \times 10^{13}$ cm^{-3}, $\tau_E \simeq 100$ ms, $Z_{eff} = 1.7$) and the electron density and temperature profiles are no longer evolving. By this time, frequent ELMs and effective helium wall conditioning limit the rate of increase of $\bar{n}_e$ ($\leq$10% of the beam fueling rate) and maintain the total radiated power from impurities at a constant level.

FEATURES OF THE LONG PULSE H–MODE

The experiments reported here were all performed in plasmas consisting of $\simeq$30% deuterium and $\simeq$70% hydrogen, with $I_p = 1.25$ MA, $B_T = 1.40$ T, and $\bar{n}_e = 2.8 \times 10^{13}$ cm^{-3} before NBI. Seven MW of neutral beam power with an approximate isotopic mixture of 25% D° and 75%H°, approximately the target plasma composition, was injected one second after the plasma initiation. The H–mode transition occurs shortly after the start of NBI, and the H–phase lasts for 5 sec until the end of the NBI (Fig. 1). After an initial rapid rise, the rate of line-averaged density rise decreases to 0.7×10^{13} cm^{-3} s^{-1}, despite an average beam fueling rate of $\sim 7 \times 10^{13}$ cm^{-3} s^{-1} [Fig. 1(c)]. Regularly spaced ELMs at a frequency of ~30 Hz occur during the H–mode phase [Fig. 1(d)]. Each ELM expels $\approx$10% of the plasma stored energy and a similar fraction of the plasma particles. At these NBI powers, no significant change was observed in ELM behavior for different X–point heights above the divertor plates, in contrast to previously observed behavior at lower NBI powers. The energy confinement time, deduced from magnetic measurements, is shown in Fig. 1(e).

Except for an initial rapid rise after the L-H transition, line intensities of the high charge states of metallic impurities [Fig. 1(f)] decrease into the H–mode while those of the lower charge states increase [Fig. 1(g)]. In agreement with these observations the gross radiated power increases rapidly during the first ELM-free period, and then is nearly constant for the remaining duration of the H–mode, with the radiation profile becoming more hollow. This behavior may be explainable by a combination of neoclassical impurity transport, a nearly flat density profile, and ELM activity. Within a few centimeters of the separatrix, neoclassical impurity fluxes would be inward, whereas, further in the interior of the plasma, due to a strong temperature gradient term, the impurity fluxes would be outward. As a result impurities may be concentrated in the plasma periphery where they are periodically expelled by ELM activity.[1]

DENSITY BEHAVIOR

A key factor for the attainment of long pulse H–mode plasmas is particle control, since an uncontrolled rise in electron density or impurity content of the plasma will ultimately lead to radiation collapse. In DIII–D, during the ELM free periods, the rate of density rise is typically 2–3 times the sum of the cold and energetic particle sources. In contrast the average rate of density rise during the H-mode is typically $\simeq$10% of the fueling rate by the neutral beams. From these observations we deduce: (a) the divertor plate surfaces act as particle reservoirs with a characteristic particle confinement time which is of the same order as the plasma particle confinement time so that the density equilibrium results from balancing significant particle transfers between the plasma and the plates, and; (b) particle loss during ELMs is a key factor in the reduced rate of density rise observed in the later phase of the H–mode.

In an attempt to explain the H–mode density behavior we have used a simple model of the particle balance in a system consisting of: the main body of the plasma within the closed flux surfaces; the scrape-off layer and divertor plasmas, and; the graphite divertor target plates, all with their respective particle confinement times of τ_P, τ_D and τ_W. The divertor plasma is the interface between the target plates and the main body of the plasma. The high divertor plasma density allows only a small fraction, α, of the particles recycling at the target plates, or particles released by the plates, to penetrate the main body of the plasma. In this model, neglecting terms of the order $\tau_\mathrm{D}/\tau_\mathrm{P}$ and $\mathrm{N_D/N_P}$, and averaging over events of a time scale $\gtrsim \tau_\mathrm{D}$, the particle content of the plasma is given by

$$\mathrm{N_P}(t) \simeq \frac{1}{\gamma\tau_\mathrm{W}}\left[\mathrm{N_T(o)} + \Gamma t\right] + \left[\mathrm{N_P(o)} - \frac{\mathrm{N_T(o)}}{\gamma\tau_\mathrm{W}}\right] \mathrm{e}^{-\gamma t} + \frac{\Gamma}{\gamma^2\tau_\mathrm{W}}\left(1 - \gamma\tau_\mathrm{W}\right)\left(\mathrm{e}^{-\gamma t} - 1\right) \ , \ (1)$$

where $\gamma = \frac{\alpha\tau_\mathrm{P} + \tau_\mathrm{W}(1-R)}{\alpha\tau_\mathrm{P}\tau_\mathrm{W}}$, R is the particle reflectivity of the divertor plates, Γ is the beam particle source, $N_\mathrm{T}(0)$ is the initial total particles in the system. The quantity $\gamma^{-1}\tau_\mathrm{W}^{-1}$ in the first term of Eq. (1) is interpreted as the fueling efficiency of the plasma. The parameter γ is the particle equipartition time constant between the plasma volume and the target plates. The last term in Eq. (1) is due to the time delay in the redistribution of the particles during fueling which is of no consequence for our present discussion.

The initial rate of density rise at the L-H transition, in excess of the beam fueling rate, arises from a sudden increase in particle confinement time, $\tau_\mathrm{p}(\mathrm{H})$, relative to $\tau_\mathrm{p}(\mathrm{L})$. This rate of density rise is given by the second term in Eq. (1):

$$\frac{\mathrm{dN_p}}{dt} \simeq \frac{\mathrm{N_T(o)}}{\tau_\mathrm{W}}\left(1 - \frac{\gamma_\mathrm{H}}{\gamma_\mathrm{L}}\right) \simeq \frac{\mathrm{N_T(o)}}{\tau_\mathrm{W}}\left[1 - \frac{\tau_\mathrm{P}(\mathrm{L})}{\tau_\mathrm{P}(\mathrm{H})}\right] \quad ,$$

where we have used $\alpha \simeq 0.1$ (see Ref. 3) and $R \approx 0.5$, and assumed $\tau_{\mathrm{P}} \approx \tau_{\mathrm{W}}$. Since $\tau_{\mathrm{p}}(\mathrm{H}) \gg \tau_{\mathrm{p}}(\mathrm{L})$, the initial rate of density rise is due to plasma absorbing all the particles released by the wall. Later in the H–mode when $\gamma t \gg 1$, $\langle(\mathrm{dN_P})/(dt)\rangle \simeq \Gamma/(\gamma\tau_{\mathrm{W}})$. Using the measured value of $\langle(\mathrm{dN_p})/dt\rangle \simeq 0.1\ \Gamma$, we obtain $\tau_{\mathrm{P}} \approx 0.5\ \tau_{\mathrm{W}}$, verifying the earlier assumption of $\tau_{\mathrm{P}} \approx \tau_{\mathrm{W}}$.

In the intervals between ELMs, the net rate of density rise is $\cong$40 Torr liters/sec, whereas the average rate of density rise is $\cong$2.1 Torr liters/sec. Neglecting particle transport during the ELM free periods compared to the average particle outflux due to ELMs, yields an effective particle confinement time of 0.5 sec, and $\tau_{\mathrm{W}} \approx 1$ sec.

ELM BEHAVIOR

ELMs are an essential factor in the attainment of the long pulse H–mode plasmas, because they not only limit the rate of density rise, but are also responsible for reducing the impurity content of the plasma. It has been shown[4] that ELMs occur when the edge pressure gradient is near the ideal ballooning mode limit, which scales as $\mathrm{I_P^2}$. In DIII–D, the ELM frequency decreases with increasing $\mathrm{I_P}$ and decreasing power. This tendency is greatly accelerated when a significant fraction of the input power is radiated in the core plasma. This is because radiative losses reduce the rate of pressure buildup, thus reducing the ELM frequency, which in turn results in more density and impurity buildup and even greater radiative losses. This phenomenon is demonstrated in Figs. 1 and 2, where the ELM behavior of two discharges with different heating power but otherwise identical external parameters are compared. In Fig. 2, the ELM frequency of a discharge with 40% lower heating power is a factor five lower than that of the reference discharge (Fig. 1). Furthermore each ELM event is followed by a 20–50 msec long L–mode period. Ultimately, due to excessive radiation, the discharge of Fig. 2 reverts to the L-mode.

Consequently, in the absence of an active particle control technique to mitigate the rate of density rise and radiative losses, it is desirable to increase the heating power or lower the plasma current. The ELM behavior in the second discharge of Fig. 2 is similar to that of JET H–mode plasmas, where the ELM free periods are long and ELMs are followed by L–mode periods. Relative to DIII–D, JET is a low power density device. Therefore JET observations[5] are consistent with the above description of the ELM behavior in DIII–D at low NBI power.

SUMMARY AND CONCLUSIONS

We have demonstrated that H–mode confinement can be sustained without impurity accumulation or confinement deterioration for times much longer than all the plasma characteristic time scales. It is shown that ELMs in conjunction with graphite divertor plates reduce the rate of density rise and radiative losses, which enable the long pulse sustainment of these discharges.

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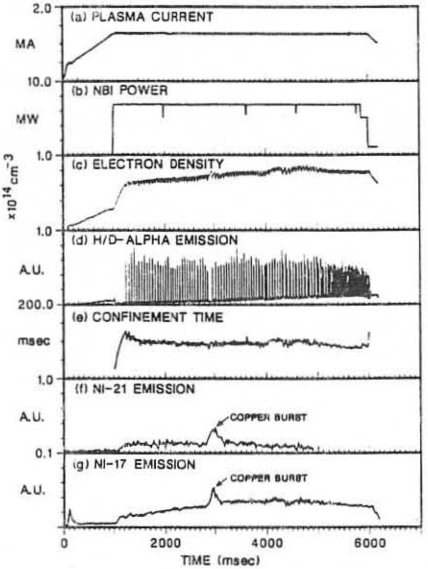

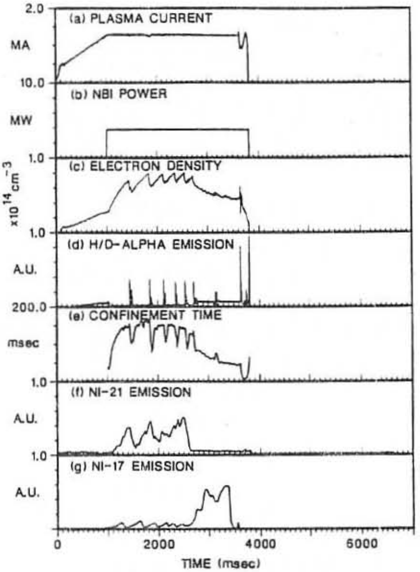

Fig. 1. Time histories of plasma parameters for quasi steady-state H–mode: (a) plasma current; (b) NBI power input; (c) line-integrated electron density; (d) H_α/D_α plasma emission from plasma divertor; (e) confinement time; (f) line emission from Ni-21 impurity near plasma center; (g) line emission from Ni-17 impurity near plasma edge.

Fig. 2. Time histories of plasma parameters for a similar plasma discharge to Fig. 1 but with reduced NBI power input. Figure quantities are the same and have the same units and scales as in Fig. 1, except for the Ni-17 line emission [(g)] which is 10 times greater than in Fig. 1.