The Density Limit in JET Diverted Plasmas

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1. Introduction

In JET limiter plasmas the density limit is associated with radiated power fractions of 100% and, in plasmas with carbon limiters, it is invariably disruptive. However, in discharges with solid beryllium limiters the limit is identified with the formation of a MARFE and disruptions are less frequent. In addition, the improved conditioning of the vessel arising from the use of beryllium has significantly improved the density limit scaling, so that the maximum density rises with the square root of the input power [1,2]. In diverted plasmas several confinement regimes exist, making the characterization of the density limit more complex. While the density limit in L-mode plasmas is generally disruptive, the limit in ELMy and ELM-free H-modes generally prompts a return to the L-mode and a disruption is not inevitable. The density limit does rise with increasing power, but the L-to-H transition complicates the analysis. Nevertheless, at low plasma currents (<2MA), densities significantly above the Greenwald limit [3] can be achieved, while at higher currents power handling limitations have constrained the range of density which can be achieved.

2. Phenomena at the Density Limit

In L-mode plasmas, the density could be raised until the radiated power fraction was ~60%, at which point the temperature in the divertor had fallen to ~10eV [4]. Subsequently a MARFE entered the main plasma from the divertor, the radiated power fraction rose to 100%, and mhd activity grew, leading to a disruption. In ELM-free H-modes, which were normal in the old JET configuration, the density rose monotonically, impurities built up in the plasma edge and the radiated power rose until it was approximately equal to the input power, with the major fraction arising from the bulk plasma. At this point, a transition back to the L-mode occurred, leading to a rapid fall in density and radiated power. In the majority of cases the fall in radiated power was sufficient to permit a return to a stable L-mode plasma and, if the input power was maintained, the H-mode could re-occur. In other cases, for example in the presence of strong gas-puffing or if the input power fell too rapidly, an L-mode density limit disruption occurred. This general behaviour was independent of whether CFC or beryllium targets were used.

ELMy H-modes, which could be established under limited conditions in the old JET configuration [5,6], were sustained in steady-state conditions on the CFC targets at radiated power fractions of up to 70%. In addition, a series of steady-state plasmas with radiated power fractions of ~100% were established using the beryllium targets [7], but in these confinement fell to L-mode levels. In high density steady-state H-modes, such as that in figure 1, small fluctuations in input power or radiation could lead to a transition in which the total radiated power fraction rose to 100% and the plasma returned to the L-mode, causing the density to decay as particle confinement fell. This is, therefore, interpreted as representing the density limit for steady-state H-modes.

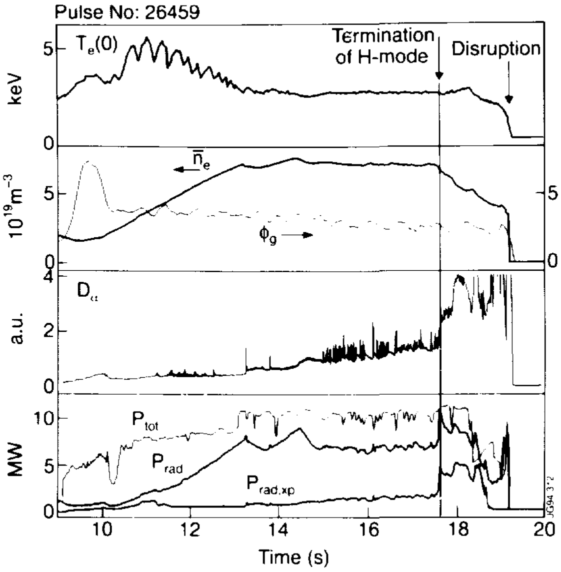

Figure 1: Overview of ELMy steady-state H-mode, terminating in a density limit disruption.

During the H-mode, the radiation was emitted predominantly from a region of ~20cm at the plasma edge. When the radiation rose to 100%, the additional radiation came mainly from the X-point region, but after a period of several 100ms, a MARFE entered the main plasma, the plasma detached fully from the divertor and evolved towards a disruption. The final disruption was not inevitable, but depended on the rate at which the plasma density and input power fell. In these plasmas the plasma density and level of radiation could be adjusted by variation of the gas-puff rate. The density limit appears, therefore, to be associated with a power imbalance, with the limiting density being determined by the input power level and radiation losses.

3. Density Limit Scaling

Following the introduction of beryllium into JET, the density limit was found to rise as $P_{tot}^{0.5}$ [1,2]. However, in some devices, the density limit is not found to scale with input power, but follows the 'Greenwald' scaling [3]. Comparison of JET data with the predictions of this scaling (figure 2) shows that at low currents (<2MA) the JET limit exceeds the Greenwald limit, but at high currents (>3MA) it falls below this. It is likely that the behaviour at high currents was caused by limitations in the power handling of the divertor targets, which restricted the duration of high power heating experiments.

For a device in which the density limit is determined by a power imbalance, such as JET, the power required to exceed the Greenwald limit increases quadratically with current, so that it is

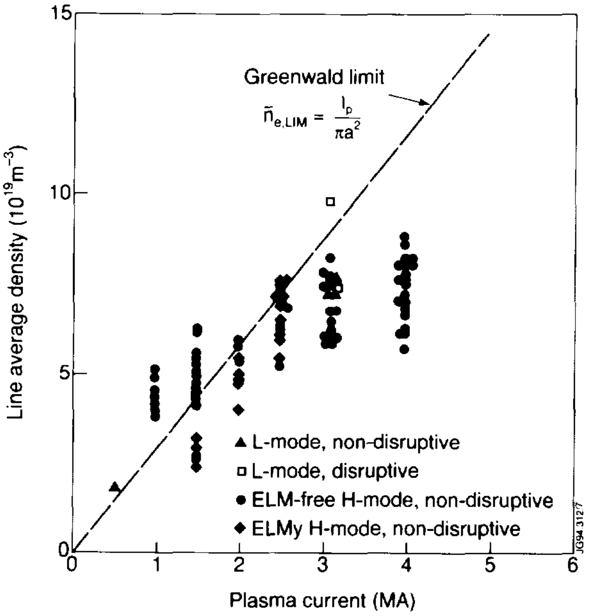

Figure 2: Comparison of densities achieved in JET diverted discharges with Greenwald scaling.

easiest to exceed the Greenwald limit at low currents. Moreover, in experiments prior to the recent upgrade, the majority of high power heating experiments were constrained to be of short duration by the occurrence of the carbon bloom. This limited the period over which the density could be raised, thereby limiting the final density which could be achieved. It is noticeable that the majority of points plotted in figure 2 were non-disruptive. This indicates that, in many cases, the density 'limit' was the highest density which could be achieved during the heating phase, rather than that at which density limit phenomena occurred. A similar pattern is found in comparing diverted plasmas with limiter plasmas: at low currents (and, therefore, moderate power), the achievable densities are similar; at high currents the 'limit' in diverted plasmas falls some 30% below that achieved in equivalent limiter plasmas, essentially because the heating experiments in diverted plasmas were of shorter duration.

4. Initial Experiments with the Pumped Divertor

Initial experiments in X-point plasmas following the recent upgrade have shown that the ohmic density limit is comparable with that observed previously, with helium plasmas reaching densities ~30% higher than comparable deuterium discharges. Figure 3 shows a 2MA plasma in which the density limit occurred with $\bar{n}_e \approx 3 \times 10^{19} \mathrm{m}^{-3}$. It can be seen that the major disruption is preceded by a rise in the radiated power fraction to 100%, the occurrence of a MARFE and the growth of an n=1 mode, all typical of disruptive density limit phenomena in previous experiments.

Figure 4 illustrates the observations made in the divertor during the approach to the limit. The central panels show measurements of the ion saturation current in the inner and outer strike regions. The modulation of the currents correspond to sweeping of the strike points at 4Hz, essentially to reduce the time averaged power deposition. This modulation, therefore, represents a sequence of time resolved profiles of ion saturation current at the inner and outer strike points during the approach to the limit. Also shown are the D_α and C-III signals for the two strike points. It can be seen that at ~12s there is a sudden reduction in the peak value of

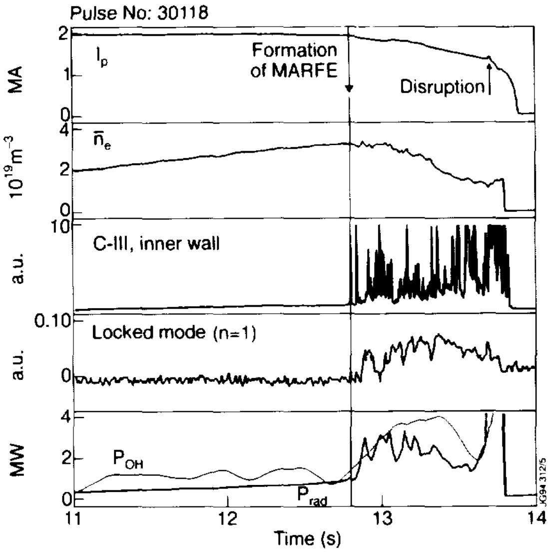

Figure 3: Overview of 2MA ohmic density limit shot in the Pumped Divertor configuration.

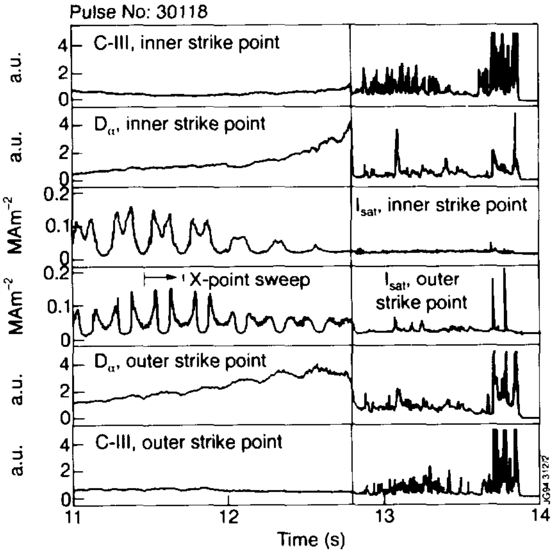

Figure 4: Divertor measurements during the approach to the density limit of figure 3.

ion saturation current which persists until 12.8s, at which time the modulation disappears and the D_α and C-III signals fall precipitately. This corresponds to the final detachment from the divertor and the entry of a MARFE into the main plasma, which is responsible for the subsequent large fluctuations on the D_α and C-III signals. However, the period between 12s and 12.8s appears to correspond to a stable period of detachment during which the X-point configuration is maintained but very little power flows to the target. These results suggest that, as in previous JET experiments [7], there may be a stable window of operation below the density limit in which the exhaust power is dissipated by radiation and charge exchange. The focus of future JET experiments will be to explore and expand this regime at high levels of auxiliary power.

References

[1] C G Lowry et al, Proc 17th EPS Conf, Amsterdam, 1990, **1** 339.
[2] K Borrass, Nucl Fusion **33** 63 (1993).
[3] M Greenwald et al, Nucl Fusion **28** 2199 (1988).
[4] S Clement et al, Proc 33rd APS Meeting, Tampa, 1991.
[5] P R Thomas et al, Proc 19th EPS Conf, Innsbruck, 1992, **1** 239.
[6] D J Campbell et al, JET Preprint JET-P(94)01 (to be publ in Plasma Phys and Contr Fus).
[7] S Clement et al, Proc 19th EPS Conf, Innsbruck, 1992, **2** 723.