Studies of Reactor-relevant H-mode Regimes in the JET Pumped Divertor

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Abstract. An extensive experimental investigation of reactor-relevant features of H-mode plasmas has been carried out using the JET Pumped Divertor. Steady-state H-modes have been established with high confinement and with durations of up to 20s. At the highest densities, these plasmas return to the L-mode when the radiated power fraction is ~50%. Detached H-modes have been produced by gas-puffing deuterium plus nitrogen, and their properties studied at total input powers of up to 32MW. Helium transport and exhaust have also been investigated, and a systematic comparison of H-modes using carbon fibre composite and beryllium divertor targets has been carried out.

1. Introduction

To achieve its goals, ITER must operate with a high confinement plasma having excellent plasma purity coupled to a divertor plasma which dissipates most of the exhaust power as radiation and charge exchange losses, while allowing adequate pumping of helium ash. Steady-state ELMy H-modes with a highly radiating divertor have the potential to provide such a scenario and the Pumped Divertor (Huguet *et al*, 1991) has equipped JET to investigate their properties. The variation of energy confinement with plasma current, edge safety factor and density has been studied in ELMy H-modes, and the transport and exhaust of helium from the plasma has been addressed. In addition, highly radiating divertor plasmas have been established by using a combination of nitrogen and deuterium puffing, and steady-state conditions maintained for up to 5s with energy confinement enhancement factors of 1.5 relative to ITER89-P scaling. The characteristics of these plasmas have been investigated using both carbon fibre composite (CFC) and beryllium divertor targets and found to be remarkably similar.

2. Steady-state ELMy H-modes

A major difference with the previous JET configuration is that H-modes exhibit regular ELM's which maintain all of the important plasma parameters in steady-state (Campbell *et al*, 1995). Such plasmas have been extensively studied under steady-state conditions lasting up to

$50\tau_E$ and $0.85\tau_R$, where τ_R is the resistive diffusion time evaluated at mid-radius. The longest pulses, with durations of 20s at 2MA, are limited only by technical constraints on the tokamak and heating systems. Global energy confinement lies in the range $(1.8\pm0.2)\times\tau_E^{ITER89-P}$, the variation being associated with changes in the main chamber recycling (Stork *et al*, 1995). No systematic dependence of energy confinement time on q_{95} is found for $q_{95}>2.1$, so that values of $H_{89P}/q_{95}>0.6$ are routinely obtained, and values of $\beta_N\sim3.7$ have been achieved for several seconds in steady-state conditions.

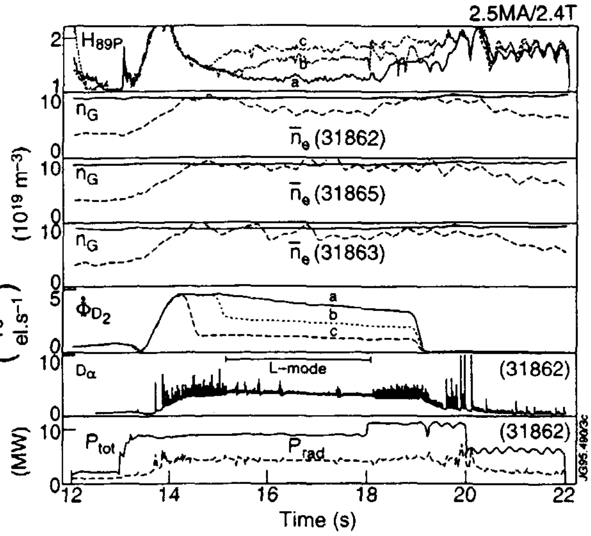

Fig.1: A sequence of 3 pulses in which the gas-puff rate was increased, eventually causing a return to L-mode confinement: (a) #31862, (b) 31865, (c) 31863.

The density in ELMy H-modes can be controlled by a combination of gas puffing and pumping using the divertor cryopump. In experiments to date, the average plasma density has been varied by a factor of 1.5, and densities equal to the Greenwald value have been maintained with high confinement (H_{89P}=1.8). As the plasma density increases the ELM frequency increases while the amplitude decreases. At the highest densities, this causes a gradual loss of confinement and, eventually, the plasma returns to the L-mode with $P_{rad}/P_{tot}\sim$40-50%, ie before divertor detachment occurs. In some case, this behaviour has been reversed by increasing the input power. Fig. 1 illustrates the evolution of density and confinement enhancement in a series of 3 discharges in which the gas puff rate was increased on a pulse-by-pulse basis. At the highest gas puff rates (corresponding to almost $1 barls^{-1}$), the plasma returned to the L-mode, as indicated by the D_α signal, and both the energy and particle confinement decreased.

3. Radiative Divertor H-modes

The low level of intrinsic radiation in JET steady-state H-modes, typically 15% between ELM's and ~30% averaged over ELM's, reflects the improved purity of plasmas in the Pumped Divertor configuration, where $Z_{eff}\sim$1-1.5 is normal. In order to dissipate SOL conducted power and demonstrate plasma regimes of interest to ITER, the use of extrinsic impurity seeding, principally nitrogen, has been extensively investigated (Matthews *et al*, 1995). The most successful approach to establishing a radiative divertor has proved to be a combination of nitrogen puffing in the divertor and deuterium puffing in either the divertor or main chamber. In this scenario, the radiated power fraction could be increased to ~80% and maintained in steady-state for periods of up to 5s. Fig. 2 illustrates a case in which an average combined heating power (NBI+ICRF) of 27MW was injected for 6s, and a total energy of 180MJ was deposited in the plasma, with ~70% accounted for by radiation. As shown in the figure, the ELM frequency increased to several hundred Hz as the radiated power increased, while the global energy confinement time fell to $\sim1.5\times\tau_E^{ITER89-P}$.

Detailed divertor measurements have shown that, during the high radiation phase, detachment occurs and the plasma parameters at the divertor targets exhibit behaviour characteristic of that observed in L-modes. That is, the ion saturation currents roll over and decrease as the main plasma density rises, and the separatrix value falls by an order of magnitude. The residual power flowing to the target is often too small to be determined by IR measurements, but in a case with 15MW of input power, the target Langmuir probes indicated that <1MW of power flowed to the target during the detached phase. A simple analysis of the radiation distribution indicates that ~2/3 comes from the 'X-point region' and that ~1/3 comes from the bulk plasma, but two-dimensional tomographic reconstructions of the radiation show that the majority of the 'X-point' radiation is emitted from a region just above the X-point (Reichle *et al*, 1995).

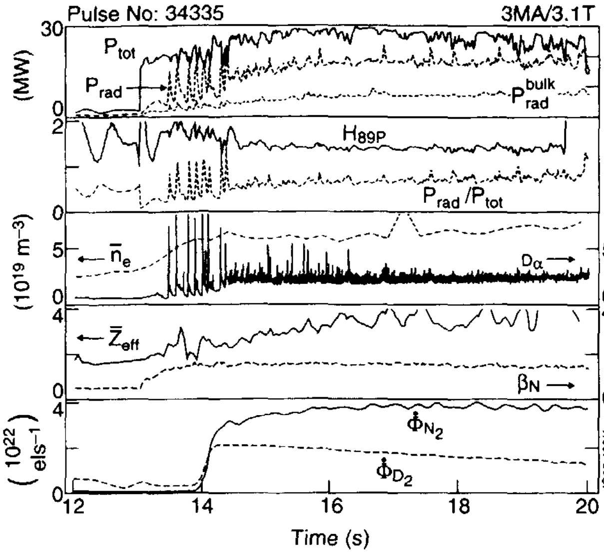

Fig.2: Overview of a radiative divertor H-mode in which an average power of ~27MW was maintained for 5s with a radiated power fraction of ~70%.

There are several attractive aspects of this regime. In particular, stable operation at high radiated power fractions has been sustained and target power fluctuations due to ELM's have essentially been suppressed. Although the confinement enhancement relative to the ITER89-P scaling law is lower than specified for ITER, that compared to ITER93-H is commensurate with that required, so that further investigations of the confinement scaling in this regime are necessary. The major outstanding problem is that, due to the migration of extrinsic impurities into the main plasma, Z_{eff} increases with heating power, and values in the range 3-4 are observed at the highest powers, far in excess of that permissible in a reactor. This is an area where much further experimentation is required.

4. Helium Transport and Exhaust

The rate at which helium ash is exhausted is a key issue for ITER, and argon frosting of the divertor cryopump allows this question to be addressed. Helium particle confinement, characterized by the global confinement time, τ^*_{He}, has been deduced from the decay of the total helium content in L- and H-modes, measured by active charge exchange spectroscopy, following a short (~100ms) He puff (von Hellermann *et al*, 1995). In cases with argon frosting, τ^*_{He} in ELMy H-modes lay in the range 8 to 15s, while in L-modes τ^*_{He} was between 4 and 10s. Cases without argon frosting yielded global particle confinement times which were twice as long. Overall, the ratio τ^*_{He} / τ_E was in excess of 20 for ELMy H-modes and greater than 10 for L-modes. The former value is greater than the value of 15 generally regarded as acceptable for ITER. However, the JET experiments were constrained by difficulties encountered with argon contamination of the main chamber, which caused disruptions and increased the deuterium poisoning of the argon layer between deposition and performance of the exhaust measurement. As a result, the pumping speed for helium was degraded by a factor of 2-3 from that measured for the fresh argon layer, ~180m^{3}s^{-1}, and this may have contributed substantially to the long helium decay times (Saibene *et al*, 1995).

5. Comparison of CFC and Beryllium Divertor Targets

The CFC divertor target tiles were replaced with Be tiles of similar design for two months of the recent experimental campaign, and a wide range of studies was performed to compare plasmas using the two materials. In general, the power handling of the Be tiles was good, although singular giant ELM's caused surface melting. H-mode plasmas exhibited few differences from those produced on the CFC target, and long steady-state H-modes (Fig. 3) and radiative divertor plasmas were routinely established. While initial spectroscopic analysis shows some detailed differences in impurity content, the level of radiation was similar and, at the highest densities, plasmas returned to the L-mode at radiative power fractions of ~50%. Thus, as in plasmas on the CFC target, detached H-modes could not be achieved with intrinsic impurities. The carbon concentration in high density plasmas did not differ greatly from that observed in plasmas on the CFC target, which may indicate that wall sputtering (the limiter and inner wall are covered with CFC tiles) was a significant source of impurities.

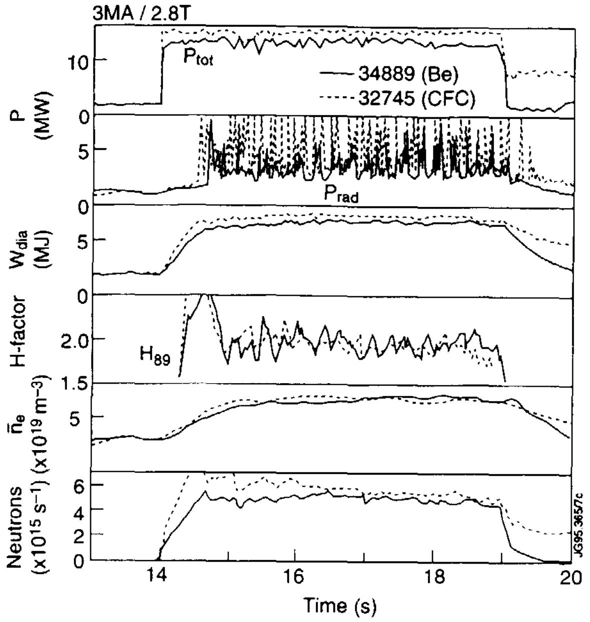

Fig.3: Comparison of steady-state H-modes using CFC and Be divertor targets.

6. Conclusions

Recent H-mode experiments in the JET MkI Pumped Divertor configuration have demonstrated that a high power plasma with good confinement, and capable of dissipating a large fraction of the exhaust power by radiation, can be maintained in steady-state. The major outstanding problem is that impurity concentrations must be reduced to an acceptable level for reactor operation, and future studies in the MkII divertor will address this issue. Further experiments are also necessary to exploit fully the argon frosting of the divertor cryopump so as to demonstrate acceptable helium exhaust in a reactor-relevant plasma regime.

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