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High Performance and High Density Steady State D-T Plasmas in JET

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1. INTRODUCTION

The quasi-steady ELMy H-mode is the preferred operating scenario for ITER. As such, a considerable fraction of the JET experimental programme in general and of the recent deuterium-tritium experiment (DTE1) more specifically has been dedicated to studying the performance and operational limits of ELMy H-modes. In this paper we describe experiments which assess the mass dependence of the performance of ELMy H-modes at the highest currents, fields and input powers currently achievable in JET, as well as of experiments designed to test the maximum density which can be achieved in ELMy H-modes with beam and gas fuelling.

2. HIGH FUSION PERFORMANCE IN ELMY H-MODES

During DTE1, JET produced ELMy H-mode discharges which are the closest approximation to ITER plasmas possible in present day machines. At 3.8 MA and 3.8 T with 24 MW of input power we have produced 22 MJ of fusion energy in a 5 s period, limited only by the duration of the heating pulse and by neutron economies (Fig. 1). This discharge reached a fusion power of more than 4 MW for 3.5 s (more than eight energy confinement times). A second discharge at 4.5 MA and 3.45 T reached even higher fusion performance (5 MW) but was terminated early by a trip in the neutral beam heating systems.

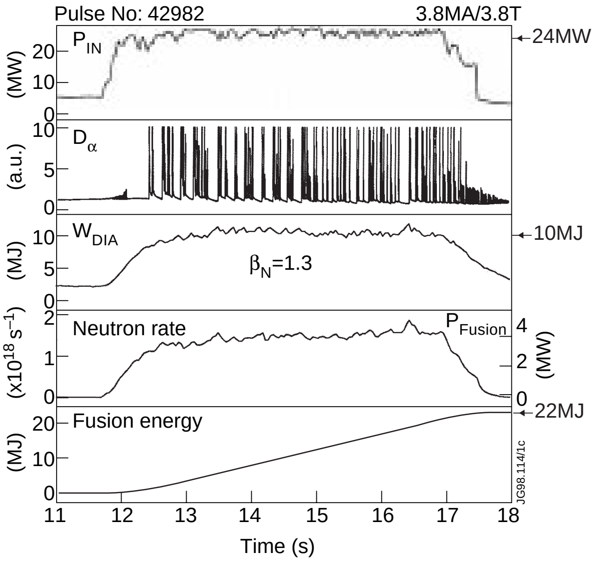

FIG. 1. Time traces of the 3.8 MA, 3.8 T ELMy H-mode which produced a world record 22 MJ of fusion energy.

The fusion Q of our 3.8 MA / 3.8 T discharge, defined simply as the ratio of the fusion energy produced to the energy input to the plasma, was 0.18 during the 3.5 s steady period. The Q of the 4.5 MA / 3.45 T discharge was 0.20, integrated over 1 s. Operation at lower q_{95} is potentially beneficial to ITER. Assuming ITER could be operated at its nomimal field but at 24 MA instead of 21 MA, our low q pulse extrapolates to a point which provides a significantly improved margin to ignition.

The confinement of high current DT ELMy H-modes is very similar to that found in deuterium preparation pulses (Fig. 2). The density of DT and T discharges is found to be somewhat higher than for similar deuterium pulses. This may be related to the lower ELM frequency which is observed in tritium pulses [1].

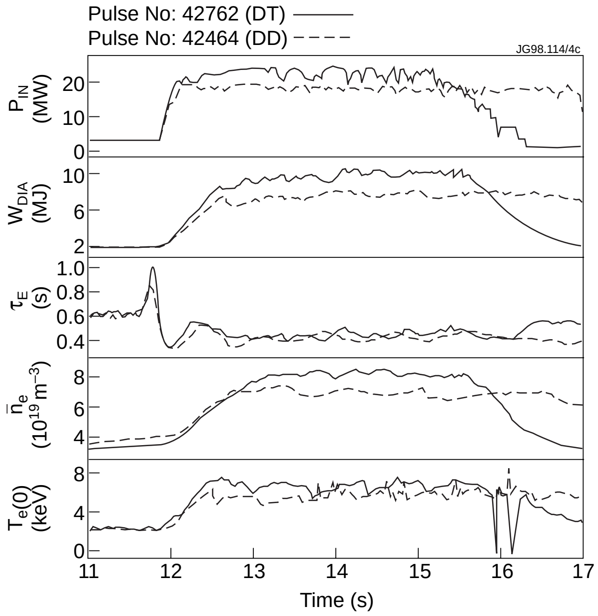

FIG. 2. Comparison of the confinement, density and temperature of two similar 3.8 MA, 3.8 T pulses, one in deuterium and one in an approximately 50:50 D:T mixture.

3. PROJECTION TO FUTURE JET PERFORMANCE

In a future DT campaign in JET it may be possible to produce a 5 MA, 4 T ELMy H-mode plasma with 30 MW of input power. Assuming that the core plasma profiles remain constant, one can separately scale the thermal and beam-thermal fusion Q's as follows:

$$Q_{th} \propto \hat{n}\hat{T}\tau_E \times \left(0.11\left(\hat{T}-5\right)+0.3\right)\left(\text{for 5 keV } < \hat{T} < 12 \text{ keV}\right) \tag{1}$$

$$Q_{b-th} \propto \frac{\hat{T}^{3/2}}{Z_{eff}^2 \hat{n}} \ (\text{fast ion slowing down time}) \tag{2}$$

where $\hat{n}$ is the central electron density, $\hat{T}$ is the central electron temperature, τ_E is the energy confinement time, and Z_{eff} is the plasma effective charge. The correction term to the normal $\hat{n}\hat{T}\tau_E$ scaling of the thermal Q is an empirical fit taking into account the non-optimum temperatures of our ELMy H-mode pulses. If one further assumes that the confinement of our DTE1 ELMy H-modes can be scaled using the 1997 ELMy H-mode scaling [2] and that the electron density scales with the plasma current but is independent of the input power, then the central plasma temperature in the projected pulse would increase from 6 keV to 7.3 keV and the peak fusion Q would increase from 0.18 to 0.29. This corresponds to the production of 9 MW of fusion power in steady state, more than 60\% of which would be thermal.

4. ELMY H-MODE DENSITY LIMIT

ITER's present design calls for operation at or above the Greenwald density limit (GDL) while still maintaining good core confinement (H_{93}≈0.85). This has proved very difficult to achieve in present-day machines where the GDL is approached only at the expense of a significant loss of confinement (H_{93}≈0.75) [3,4]. Experiments in plasmas which have a large tritium fraction (≈90%) have shown that this result does not depend strongly on ion mass. In Fig. 3 the peak edge electron temperature, just before the ELMs, is plotted versus the peak edge electron density for two series of ELMy H-mode discharges, one in deuterium and one in tritium. The tritium discharges reach a somewhat higher edge pressure than the deuterium shots. In both cases the variation of the edge density with gas fuelling is weak.

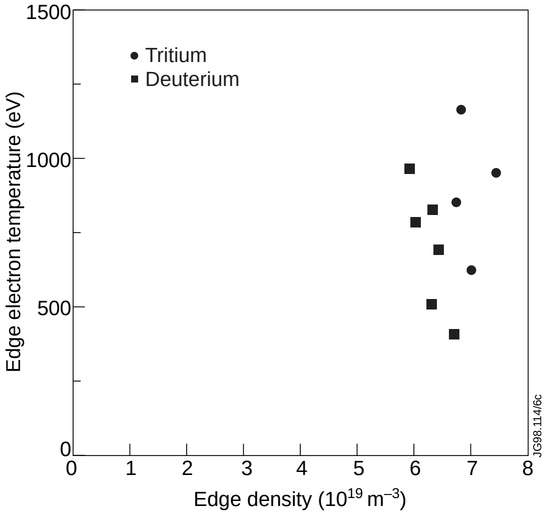

FIG. 3. Peak edge electron temperature (just before the ELM) versus peak edge electron density for a series of pulses in deuterium and tritium. The gas fuelling rate is varied from one pulse to another; each point represents steady conditions in a given pulse.

5. MASS DEPENDENCE OF THE L-MODE DENSITY LIMIT

The ultimate, disruptive density limit in X-point plasmas is due to a thermal instability which begins in the divertor. The scaling of this limit with isotope mass has been tested for Ohmic discharges (Fig. 4). The density limit is found to decrease with increasing isotope mass, in agreement with two dimensional fluid code predictions [5] and in contrast to the results reported above for the ELMy H-mode density limit.

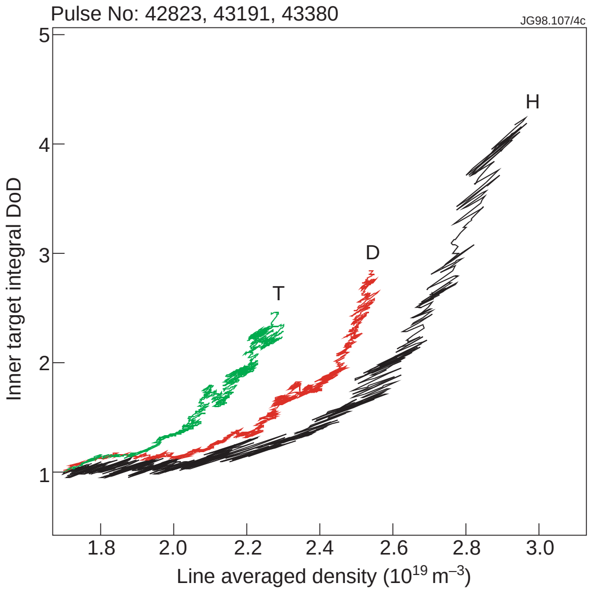

FIG. 4. Inner target degree of detachment versus central line averaged electron density for three Ohmic density limit pulses showing the dependence on hydrogen isotope.

6. SUMMARY AND CONCLUSIONS

High performance ELMy H-mode plasmas, the reference scenario for ITER, have been demonstrated in DT mixtures. 22 MJ of fusion energy has been produced in a single pulse, limited only by the duration of the heating pulse and by the available neutron budget. In our highest current DT pulse (4.5 MA), 5 MW of steady fusion power was produced with approximately one third of this being thermal fusion. Projections based on our best pulses show that, following upgrades to JET, it should be possible at 5 MA and 4 T, with 30 MW of input power, to produce almost 10 MW of fusion power in a future JET DT programme.

The confinement of our high current DT pulses is similar to that in DD although the density of the DT pulses is somewhat higher and the ELM frequency somewhat lower. These results have been confirmed in more detailed studies at lower current [6].

In tritium, as in deuterium, it is difficult to raise the density of neutral beam fuelled ELMy H-modes using gas puffing and the increase which is possible occurs at the expense of degraded confinement. There is some increase in the density and pressure obtained at the top of the edge confinement barrier in tritium as compared to deuterium. This has been postulated to be due to a dependence of the transport barrier width on the Larmor radius of either the thermal or the fast ions in the plasma edge [1].

The disruptive density limit has been tested in Ohmic and L-mode plasmas and its dependence on mass assessed. The density limit is shown to decrease with increasing isotope mass, in agreement with predictions using 2D fluid code simulations. The different scaling of the L and H-mode density limits suggests that they are due to different physical mechanisms.

[1] J. Lingertat et al., Proc. 13th Int. Conf. on Plasma Surface Interactions, to be published in J. Nucl. Mater.

[2] ITER Confinement Database and Modelling Working Group (presented by J .G. Cordey), Plasma Physics and Controlled Fusion 39 (1997)

[3] G. Saibene et al.“Steady state H-modes at high plasma density in JET,” in Controlled Fusion and Plasma Physics (Proc. 24th Eur. Conf. Berchtesgaden, 1997), volume 21A, p.49, Geneva, 1997, European Physical Society, Part I.

[4] G. Saibene et al., Paper P1-008, this conference.

[5] C.F. Maggi et al. “The Isotope Effect on the Disruptive Density Limit in JET H, D, and T Divertor Plasmas”, to be submitted to Nucl. Fusion. \newline

[6] K. Thomsen et al., Paper To-40, this conference.