Simulations of JET Hot-ion H-modes with a Predictive Code

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1. INTRODUCTION

The $1^1/_2$-D predictive code PRETOR [1] has been modified to include, among other things, neutral beams [2]. PRETOR has been used to simulate the JET hot-ion H-mode. This mode is obtained by injecting high power neutral beams into a low density plasma. This results in a hot plasma ($T_i \approx 20$ keV, $T_e \approx 10$ keV) which exhibits almost linearly rising stored energy, plasma density and neutron yield, until a termination event limits the performance [3].

Simulations of hot-ion H-modes considering different levels of recycling, various beam energies and deuterium and tritium beams will be described in this paper. A limiting pressure gradient (based on ballooning modes) and a limiting edge current density (based on external kink modes) have been considered in the modelling and are discussed. The simulations point the way to possible improvements in performance.

2. DESCRIPTION OF THE PRETOR MODELLING

Recent additions to PRETOR include a mixed Bohm - gyro Bohm transport model for the bulk transport and a one poloidal Larmor radius wide neoclassical H-mode transport barrier at the plasma edge [4,5]. The following leading terms in the edge can be identified:

H-mode barrier width: $$\rho_\theta = 0.457\frac{\sqrt{AT_i}}{B_{pol}} \quad \text{(cm, keV, T)} \qquad (1)$$

Heat and particle diffusivity: $$\chi_i = \chi_e = D \sim \frac{n_i\left(Z_{eff} - 0.7\right)}{\sqrt{T_i}\,B_{pol}^2} \quad (\text{m}^2/\text{s},\ 10^{19}\ \text{m}^{-3},\ \text{keV, T}) \qquad (2)$$

Heat flux $$q_{\text{heat}} \sim \frac{n_i^2\left(Z_{eff} - 0.7\right)}{\sqrt{A}\,B_{pol}} \quad \text{does not depend on temperature} \qquad (3)$$

Due to (3) the stored energy of a hot-ion H-mode can grow almost linearly in time until heat losses proportional to n^2 and Z_{eff} become comparable to the input power.

3. SIMULATION OF THE HOT-ION H-MODES

JET's neutron yield record shot 33643 (3.75MA/3.4T) has been modelled, keeping the volume average density evolution ($<n_e>(t)$) equal to the experiment: $d<n_e>/dt = 1.29\ \phi_{nbi}$. Time traces for $<n_e>$, Z_{eff}, total stored energy W_{tot} and D-D reaction rate R_{DD} are given in figure 1. Experimentally, the termination occurred at 13.38 seconds. This was simulated by increasing Z_{eff} at 13.38 seconds in line with the experimental Z_{eff} derived from charge exchange spectroscopy. An increase in Z_{eff} is modelled by puffing "carbon gas" into the edge of the discharge, so the *edge* Z_{eff} is even higher than the average Z_{eff} in figure 1, leading to a big increase in the heat loss (3) and irreversible termination of high performance.

There are also successful simulations of a hot-ion H-mode at 1.7MA / 1.5T (34488) and shots where the beam power decreased stepwise after $^1/_2$ or 1 second.

4. INFLUENCE OF THE RECYCLING

Plasma edge recycling of neutrals is quantified in this paper as the excess density rise over beam particle fuelling. It affects the performance because additional cold input gas must be heated. It also leads to higher density, increasing the particle/heat fluxes leaving the plasma (3) and reducing beam penetration. Improvements in performance are expected if excess edge fuelling can be reduced. Figure 2 shows two simulations of a plasma with the same equilibrium, power input and target density as 33643. One corresponds to the measured excess fuelling of 0.29, the other assumes no excess fuelling (every particle leaving the plasma is returned). No termination is assumed. It can be seen that stored energy and neutron yield reach much higher values for the low recycling case.

5. TARGET DENSITY PROFILE PEAKING

Two simulations were done using different values for the density in the plasma centre n_e (0), but with identical volume average densities $<n_e>$ at the start of the H-mode at 12.15 seconds, to test the effects of target density profile peaking. Centrally deposited beam particles diffuse towards the edge where the H-mode barrier prevents most particles from leaving the plasma. The two simulations (figure 3), showing cases with a very peaked and flat density profile appear to reach the same density profile in less than a second: *core particle transport wins over beam fuelling*. Indeed, experiments with peaked target density profiles have never yielded significant benefits over modestly peaked target density profiles.

6. PARAMETERISATION OF HOT ION H-MODE TERMINATION

Ballooning modes [6] and the external kink [7] impose a limit on the pedestal energy W_{ped} that can be sustained by the H-mode barrier. For the ballooning limit we have:

$$\frac{\nabla p}{\nabla p_{\max}} \sim \frac{W_{ped}/\rho_\theta}{B_{pol}^2} \sim \frac{W_{ped}}{B_{pol}\sqrt{AT_i}} \Rightarrow W_{ped} < Const\, B_{pol}\sqrt{AT_i} \tag{4}$$

All quantities in (4) refer to the edge. The giant ELM terminating some hot ion H-modes is thought to be a ballooning limit [3,6]. The "outer mode", which occurs in other hot ion H-modes is thought to be related to the external kink [3]. For this mode, the fraction of edge current related to total current is the critical parameter. If the edge current arises solely from the bootstrap current one has, using a simple expression for the bootstrap current [8] and the H-mode barrier width given by (1):

$$\begin{aligned} \frac{I_{boot}^{edge}}{I_{tot}} &\sim \frac{\rho_\theta\, j_{boot}^{edge}}{B_{pol}} \sim \frac{\rho_\theta (T_e + T_i) q \nabla n_e / B}{B_{pol}} \\ &\sim \frac{W_{ped}}{B_{pol}^2} \Rightarrow W_{ped} < Const\, B_{pol} \end{aligned} \tag{5}$$

The maximum pedestal energy achievable appears to be a function of the plasma current. The pedestal energy could conceivably be increased by driving an edge current in the opposite direction, e.g by *current rampdown.*

Simulations based on the present 33643 equilibrium; NBI power and target density are shown in figure 4, giving the D-D Reaction rate for various values of $d\langle n_e \rangle/dt$ and termination assumptions. The terminations pose a significant limitation to performance.

With lower recycling, modest improvements in performance are possible. Larger improvements can only be obtained if the ballooning limit can be increased (e.g. by using a more favourable magnetic configuration) ***and*** by using current rampdowns to delay the external kink.

7. DEPENDANCE ON BEAM INJECTION ENERGY

The mix of 13MW of 80 kV and 8 MW of 140 kV beams installed at JET is not suited for experiments on varying the beam energy in a hot ion H-mode, whilst keeping the total power constant. With PRETOR, however, we simulated 15 MW 80 kV NBI and 15MW 120 kV NBI cases (fig. 5). The high-energy beam case has a lower particle influx and reaches significantly higher stored energy and neutron yield than the low-energy beam case. Termination was by the "external kink" in the 120 kV beam case and by "ballooning" in the 80 kV beam case.

8. TRITIUM BEAMS

The present JET Experimental Programme includes a phase of DT plasma operation (Deuterium Tritium Experiment 1 - DTE1) to begin at the end of 1996. The tritium will mainly be supplied with the high energy neutral beams at JET ($E \approx 140$-160 keV). The use of tritium beams has several effects on the hot ion H-mode:

- More power. Available beampower will rise from 21 MW to 24-26 MW.
- Lower beam fuelling per MW injected power. This also means that the tritium concentration in the plasma is expected to remain low ($\approx 30\%$).
- More plasma ion heating from the tritium beams.
- Power from α-particle heating provides plasma heating without associated density rise.
- An isotope effect arises from the H-mode barrier width (1).

All these effects increase the fusion performance and stored energy. Figure 6 shows simulations with tritium beams in a 33643-like plasma. In all cases the same ballooning and kink termination limits were kept as for 33643. No current ramps are applied. Stored energy, D-T neutron yield ($P_{fus}=2.82 \cdot 10^{-12}\, R_{DT}$) and tritium concentration are shown for:

- 25 MW NBI, consisting of 12 MW 160 kV T-beams and 13 MW 80 kV D-beams.
- 19 MW NBI consisting of 10.5 MW 150 kV T-beams and 8.5 MW 80 kV D-beams.
- 19 MW NBI consisting of 7.5 MW 140 kV D-beams and 11.5 MW 80 kV D-beams.

From fig. 6, performance can be expected to be higher with the tritium beams, even without invoking improvements to recycling and MHD stability.

9. CONCLUSIONS

PRETOR has proven to be suitable for simulating a variety of JET hot ion H-mode discharges and the following experimental observations were successfully simulated:

- Low recycling is beneficial for high performance.
- A peaked target density profile will flatten quickly in the hot ion H-mode.
- The increase in edge Z_{eff} observed in most terminations causes it to be irreversible.

The following predictions have been made:

- Low recycling improves the ballooning stability at the edge.
- Current ramp-down can be used to improve the kink stability.
- Increasing the beam energy leads to higher performance.
- Tritium beams increase the plasma stored energy due to a variety of reasons (sect. 8).

REFERENCES

[1] D Boucher and P-H Rebut, Proc. IAEA Techn. Comm. meeting on Adv. in Simulation and Modelling of Thermonuclear Plasmas, Montreal, Canada, 1992. IAEA Vienna (1993) 142.

[2] H P L de Esch et al, Fusion Engineering and Design 26(1995)589 or JET-P(93)103

[3] T T C Jones and the JET team, Plasma Phys. Control. Fusion 37(1995)A359

[4] V Parail et al, JET-P(95)49, to be published in Plasma Phys. and Control. Fusion.

[5] A Cherubini et al, This conference.

[6] T C Hender et al., Proc. 22nd Eur. Conf. on Contr. Fusion and Pl. Phys. (1995) 19C prt I p. 29

[7] G T A. Huysmans et al., 22nd Eur. Conf. on Contr. Fusion and Pl. Phys. (1995) 19C prt I p. 201

[8] J Wesson, Tokamaks (page 95). Oxford, Clarendon Press, 1987

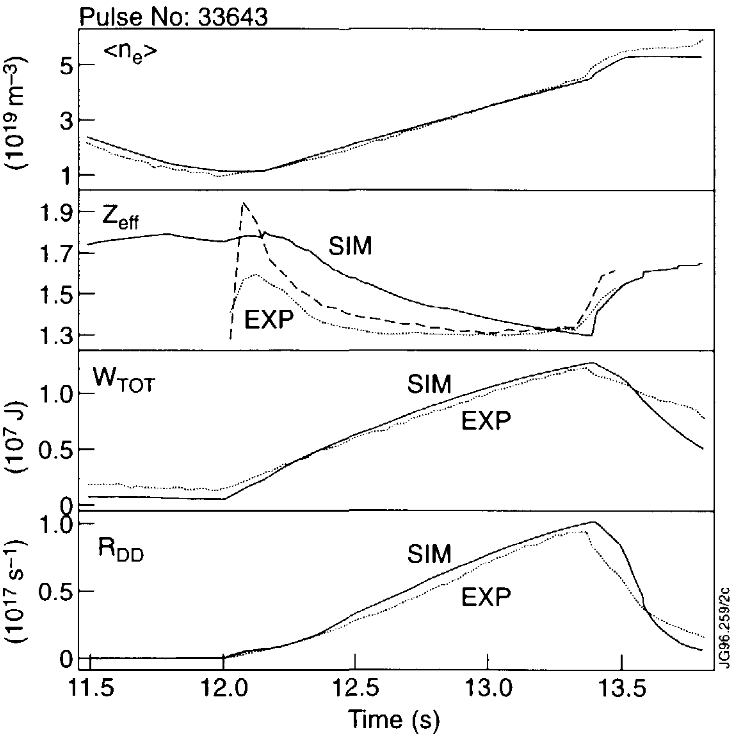

Fig. 1: Volume averaged density, Z_{eff}, Stored energy and D-D reaction rate for shot 33643. Simulation vs. Measurement

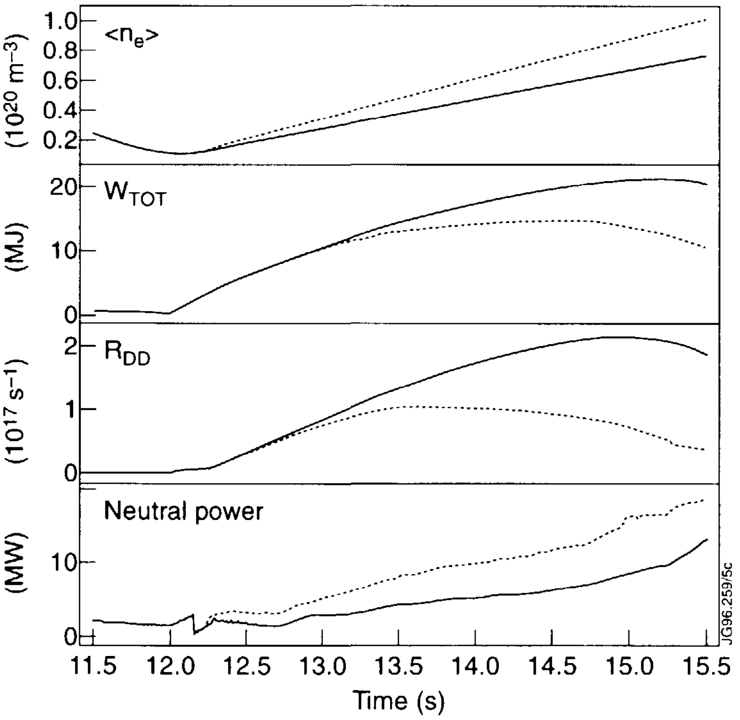

Fig. 2: Simulated density, Stored energy, D-D reaction rate and Power to heat neutrals: Solid lines: $d<n_e>/dt = \phi_{beam}$, dashed lines: $d<n_e>/dt = 1.29\ \phi_{beam}$.

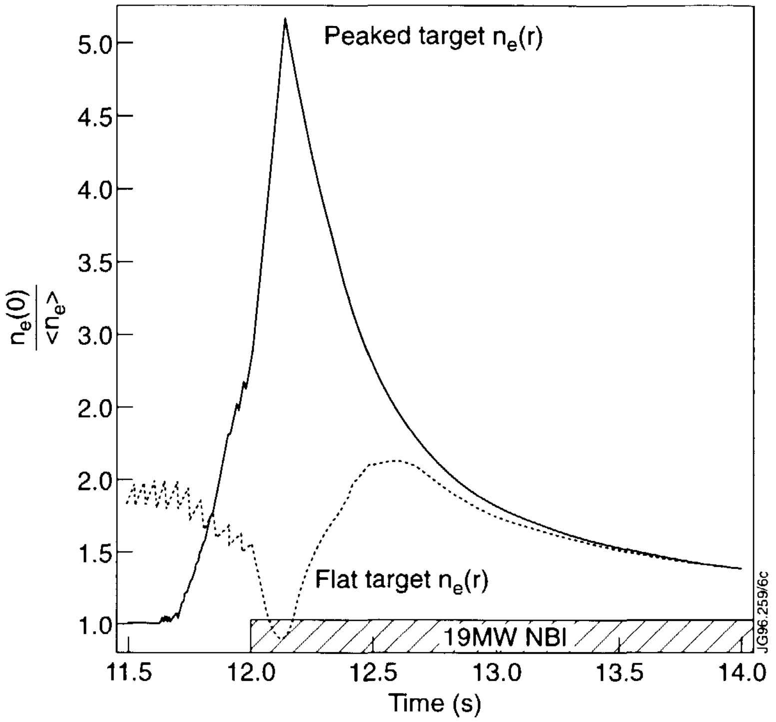

Fig. 3: Density profile peakedness ($n_e(0)/<n_e>$) evolution for two simulations: Solid line: Extremely peaked target density profile at the start of the H-mode. dashed line: Flat target density profile at the start of the H-mode.

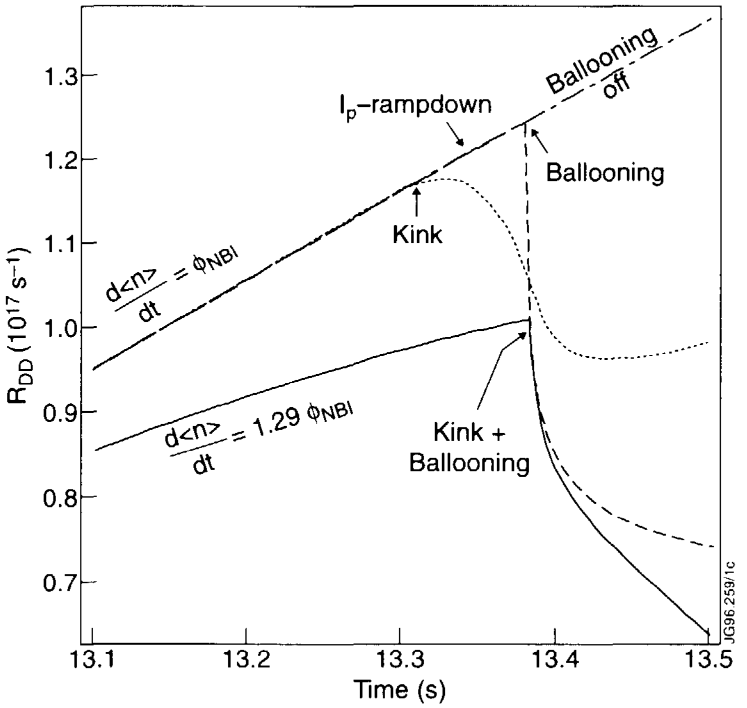

Fig. 4: Simulated D-D Reaction rates: Solid line: Benchmark for kink and ballooning. dotted and dashed lines: dotted: Kink and ballooning enabled. dashed: Current ramp to forestall kink dot-dash: Ballooning switched off

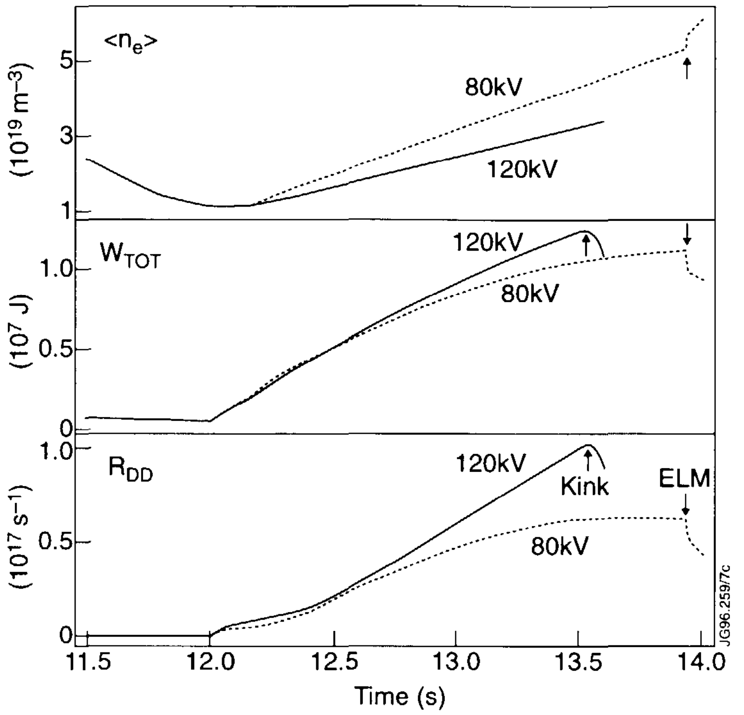

Fig. 5: Density, Stored energy and D-D Reaction rate for two 15 MW hot-ion H-mode simulations. Solid line: 120 keV Beams (kink termination) Dashed: 80 keV Beams (ballooning termination)

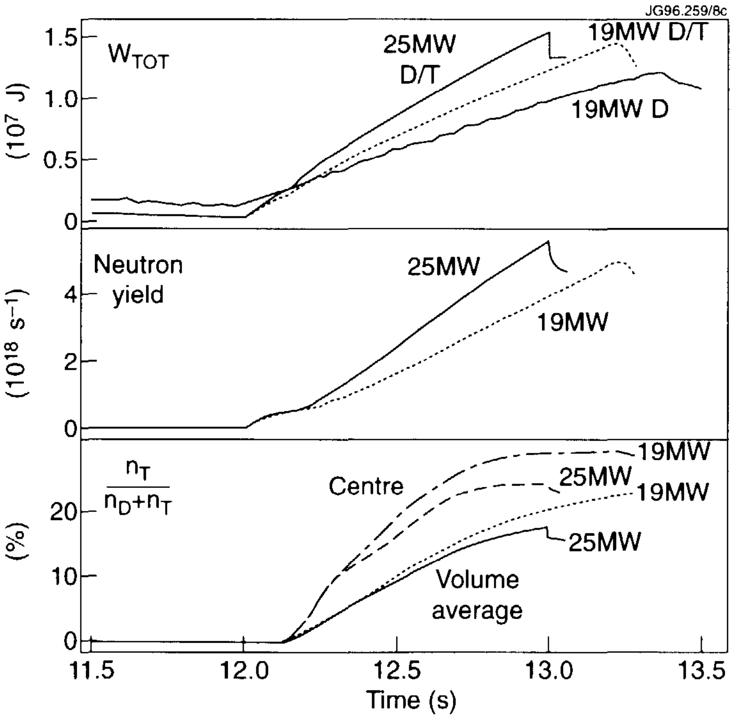

Fig. 6: Stored energy, D-T Neutron yield and tritium concentration for 25 MW D/T beams (solid lines) and 19 MW D/T beams. The experimentally measured stored energy using 19 MW deuterium beams is also indicated.