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A Power Step-down approach to High Performance, Steady-state Operation with ELM-free H-mode Deuterium Plasmas in JET

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ABSTRACT

This paper discusses the power step-down approach to steady-state operation of deuterium plasmas in the hot-ion ELM-free H-mode of the JET tokamak. Being ELM-free, when full heating power is maintained, these plasmas are usually transient and terminate with a variety of MHD phenomena. With power step-down, instabilities are delayed or avoided and nearly constant plasma conditions at up to 10 MJ of stored energy are maintained by 10 MW of heating power for up to 1 s, about an energy confinement time at 3.5 MA and 3.4 T. Global ELM-free H-mode confinement scaling is examined in this regime, without recourse to large transient corrections. The confinement times increase after the transition to quasi-steady conditions, and are some 10-25% above the scaling law predictions, with the same parametric dependence. Code simulations of the experimentally observed neutron rate and the lack of a major discontinuity in the rate before and after power step-down confirm that neutron production is predominantly (>60%) from thermal fusion. The scaling of fusion rates from deuterium plasmas to deuterium-tritium mixtures implies a fusion Q approaching 1, and alpha particle heating which exceeds beam heating and ion-electron exchange in the core electron power balance. The constant edge pressure gradient contributes to the improved edge mode stability of these discharges. The Giant ELMs which usually terminate the discharge seem to be the result of a slowly evolving current density profile. Optimisation experiments indicate that the stored energy and neutron production are maximised and the density rise minimised by preferentially retaining the JET high energy 140 keV beams. The plasma remains in an ELM-free H-mode even when the heating power after step-down is lower than the L-H transition power. Thus, the power step-down method provides a significant advance towards the regime of steady-state high performance and will be utilised in future D-T experiments.

1. INTRODUCTION

This paper focuses on experiments that extend the duration of high performance deuterium plasma discharges in the hot-ion ELM-free H-mode regime in JET towards more steady-state conditions, by using a power step-down method which may be generally applicable to high performance regimes. Such discharges, which normally stay at their maximum parameters for only a few 100 ms (less than an energy confinement time), are maintained in near steady conditions for an energy confinement time or longer. The extended discharge quiescent period and reduced heating power have several advantages as shown below.

Several tokamaks are investigating high performance regimes, with large plasma stored energy and high fusion neutron rates, in either deuterium (D-D) or deuterium-tritium mixtures (D-T). The highest performance discharges are transient and maximum heating power is applied until an instability limit is reached [1,2]. Examples include the hot-ion H-mode, supershot, reversed shear, and VH-modes [3-9]. In the JET tokamak, hot-ion ELM-free H-mode plasmas are characterised by central ion temperatures of 15-30 keV, electron temperatures of 10-14 keV, and densities of $2\text{-}5 \times 10^{19}$ m^{-3}. Steady-state discharges are also being investigated in many tokamaks. However, these discharges, obtained using a limiter or in a divertor regime with repetitive ELMs [10], tend to have somewhat lower performance.

Extensive effort has been devoted to understanding the underlying transport physics of the global and local energy balance of high performance discharges, and to extrapolating to future experiments. The accuracy of the analysis of local transport in transient discharges is reduced by the presence of beam heating terms much larger than the power lost from the plasma and large time derivatives of plasma energy components, which prevent the thermal transport rates from being the largest terms in the transport equation. In global confinement analysis, similar considerations apply to the calculation of the energy confinement time, especially when such discharges maintain high performance for a shorter duration than the inferred confinement time. Regrettably, ELM-free confinement time scaling relies upon such transient data. These uncertainties are considerably ameliorated in the quasi-steady conditions discussed in this paper.

Measurement of the neutron production, including spatial profiles, from fusion in D-D and D-T plasmas provides a method for verifying the consistency of kinetic calculations of beam and thermal ion densities and temperatures. In plasmas where the beam ion density is much larger than it would be in steady-state conditions, or when the neutron emission is dominated by beam-thermal emission, the calculation of fusion Q in D-D and extrapolation of Q to D-T involves several assumptions about how the different fusion source components and their time derivatives are to be treated. Thermal fusion is the largest source of neutron production in step-down discharges, so many terms with large measurement uncertainties become small rather than dominant, and the extrapolation to D-T is more certain.

Non-steady conditions and unnecessarily high auxiliary heating power are even more deleterious in the search for the effects of alpha heating power on the plasma energy balance in D-T experiments. In the first experiments in JET [11-13], fusion powers at the megawatt level resulted from 10% tritium concentrations in the plasma, so the alpha production power was only about 1/50th of the heating power. In these transient discharges with large injected heating power, high neutron rates were maintained for only a fraction of a second, often less than the inferred energy confinement time. In TFTR, plasmas with larger tritium fractions yielded total fusion powers of 10.7 MW in the transient supershot regime, including 2.1 MW of alpha particle power, from an injected beam power of 39.5 MW. The alpha power represented about 1/18th of the heating power, making it difficult to detect the alpha heating. In transient hot-ion ELM-free H-modes in JET, when extrapolated to d-t operation, the alpha production power would represent up to 1/7th of the beam heating power. Based upon preliminary step-down D-D experiments in JET [14], extrapolation to D-T conditions would give a fusion power comparable to the heating power, and hence an alpha production and heating power, with sufficient time for alpha thermisation, of about 1/5th of the heating (about equal to the loss) power, which would become larger than beam heating and ion-electron transfer in the electron power balance.

The determination of the mechanism and triggers of instability and termination can be obscured in transient discharges, since many relevant parameters are evolving rapidly and simultaneously, including the pressure gradients and current density profile everywhere in the plasma. Quasi-steady discharges allow these key parameters to evolve at slower and different rates, particularly at the edge.

In this paper, step-down discharges are analysed to provide insights into the plasma energy balance and its scaling, neutron production sources and extrapolation to fusion power production, discharge termination mechanisms, and optimisation of quasi-steady-state discharges. An extensive analysis is provided of the initial experiments [14], and of subsequent step-down discharges produced in JET with a view to further discharge optimisation.

In Section 2, the general properties of quasi-steady hot-ion ELM-free H-mode plasmas produced by step-down in the JET Mark I divertor are discussed and compared to more transient discharges where full heating power is continuously applied. The changes introduced by operation in the more closed Mark II divertor are also presented, with emphasis on the changes in plasma density evolution (see also Section 3). The characteristic time scales of the plasma are calculated to demonstrate that quasi-steady conditions are obtained.

Section 3 considers the macroscopic energy and particle balance and components of power loss in these plasmas. It is shown that the plasma loss power varies weakly across the power discontinuity at step-down, hence the state of confinement does not significantly change, allowing these discharges to reach quasi-steady conditions by a power step-down to the loss power level. These discharges provide a unique opportunity for comparing measurements of energy confinement times, determined from times as long or longer than the energy confinement time, with ELM-free scaling laws. An analysis shows that the step-down discharges do indeed conform to ELM-free confinement time scaling within the error bars of the scaling laws, although with some difference in magnitude before and after the step-down. In a TRANSP simulation of the profile evolution of a step-down discharge, the elimination of the transient terms makes it possible to demonstrate that the thermal ion power balance in the core is dominated by beam heating and ion conduction losses after the step-down.

In Section 4, the neutron emission sources are determined by direct observation and code simulation. It is observed that the fusion power is not greatly diminished by eliminating a large fraction of the beam heating power, and that therefore the discharge neutron production is dominated (>60%) by thermal fusion, and this is confirmed by TRANSP code simulations. The equality of the heating and loss power, and the magnitude of thermal fusion, remove many ambiguities in the calculation of the fusion Q, which approaches 1 in an extrapolation to deuterium-tritium operation. The power step-down also enhances the relative importance of possible alpha particle heating effects.

An example of the role of step-down discharges in termination studies is given in Section 5, where it is shown that a Giant ELM termination can occur in the presence of an edge pressure gradient which is essentially static, and the residual evolution is in the current profile. The effects of sawtooth crashes are also investigated.

Section 6 describes several experimental studies for further optimising the performance of these discharges. A particular problem is that the electron density in ELM-free H-mode plasmas usually increases continuously. Attempts to resolve this problem with optimum beam particle fuelling and recycling control are discussed. The plasma also needs to remain in the H-mode to maintain high performance, and the limits of this are investigated.

Conclusions are drawn in Section 7.

2. GENERAL PROPERTIES OF QUASI-STEADY ELM-FREE PLASMAS

In this section, the general properties of quasi-steady hot-ion ELM-free H-mode plasmas produced by step-down in the JET Mark I and Mark II divertor are discussed and compared to more transient discharges where full heating power is applied continuously.

Fig.1 shows the main discharge parameters for the step-down discharge with the highest sustained neutron production in the JET Mark I divertor configuration, Pulse 34236, with a plasma current of 3.5 MA and a toroidal field of 3.4T, compared with the more transient Pulse 33643 at 3.8 MA and 3.4 T. After establishing a low density plasma target, a heating power of 19 MW applied to both discharges for about 1 s produces hot-ion ELM-free H-mode discharges [3,15].

After reaching a stored energy of 10 MJ in Pulse 34236, the heating power is stepped down to about 10 MW (its loss power) and produces a quasi-steady ELM-free H-mode plasma. The plasma remains ELM-free for a further second, with slow variations in the plasma density, neutron rate and stored energy. The axial ion temperature declines slowly towards the axial electron temperature. Nevertheless, the discharge terminates due to a Giant ELM as shown on the D_{alpha} light signal. Just before step-down, the ion temperatures of both Pulse 33643 and Pulse 34236 equal about 23 keV. Just after step-down, the ion temperature falls in Pulse 34236 due to the reduction in ion heating. The global neutron rate maximum in Pulse 34236 is 2/3 of the maximum in Pulse 33643, which occurs at a later time and at a higher stored energy. The axial electron densities, shown as measured by an interferometer array and confirmed by LIDAR laser scattering, equal $3.4 \times 10^{19} m^{-3}$ at 12.9 s, just before the step-down. Afterwards, the density increases less in Pulse 34236 in accordance with the lower fuelling rate.

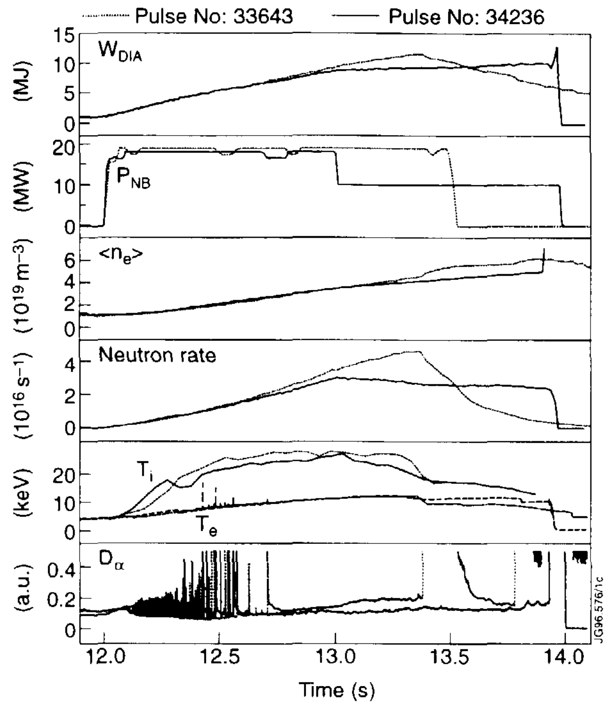

Fig.1: The stored energy from the diamagnetic loop, injected neutral beam power, volume averaged density from interferometry, global neutron rate from fission chambers, central ion and electron temperatures from CXRS and ECE, and Dalpha recycling light for full power Pulse 33643 and power step-down Pulse 34236 in the Mark I divertor configuration.

The characteristic time scales in the plasma are calculated, to demonstrate that quasi-steady conditions are obtained. Various time scales characterise the residual rates of parameter evolution after power step-down. Table I gives the central and global parameters and time scales of Pulse 34236 at 0.2 s after beam step-down. The time scales computed at the plasma axis are short compared to the 1 s duration of the quasi-steady phase. In an equivalent D-T plasma producing 3.5 MeV alpha particles, the slowing down time would be comparable to the duration of the quiescent period, and hence their energy deposition power in the plasma would tend towards equilibration with their production power.

The global electron-ion equilibration times and energy confinement times equal about 1 s, so the electron and ion temperatures are slowly equilibrating while the plasma energy is in a quasi-steady condition. The slow density increase also tends to equilibrate ion and electron temperatures, but the ion density-temperature product maintains a neutron rate changing more slowly than the ion temperature. The plasma density doubling time, due to the beam fuelling and to neutral influx from the vacuum vessel and divertor regions, is twice the discharge duration after step-down.

Table I. Central and Global Parameters and Time Scales of 34236.

Central Parameters	**Value**
Data time (s) [Heating begins at 12.0 s]	13.2
Electron Temperature (keV)	12.3
Ion Temperature (keV)	20.9
Electron Density (10^{19} m^{-3})	3.9
Deuteron Density/Electron Density	0.96
Global Parameters	
Plasma Stored Energy (MJ)	9.6
dW/dt (MW)	1.6
Injected Beam Power (MW)	10.0
Total Loss Power (MW)	8.0
Ratio of Volume Density Increase to Beam Fuelling	1.5
Axial Time Scales (s)	
Beam Slowing Down to 1/e from 140 kV	0.2
Beam Slowing Down to 1/e from 80 kV	0.1
140 kV beam-thermal fusion reactivity to 1/e of max	0.2
80 kV beam-thermal fusion reactivity to 1/e of max	0.1
Alpha Slowing Down to 1/e of 3.5 MeV	1.2
Global Time Scales (s)	
Total High Performance Phase	2.0
Total Quasi-steady Phase after step-down	1.0
(Thermal Electron) - (Thermal Ion) Equilibration	1.0
Global Energy Confinement	1.2
Plasma Energy Doubling Time	6.0
Plasma Density Doubling Time	2.4

The Mark II divertor configuration most recently installed in JET has a more closed geometry and better recycling control than the previous Mark I. Fig.2 shows the step-down Pulse 38666 produced with 16 MW of neutral beam heating plus 3 MW of mixed resonance ICRF (two frequencies delivering half the power on axis, half midway out), which comprised the total heating power during the first second. Gas puffing during the entire discharge produces a higher density and reduces shinethrough losses as compared to Pulse 34236, resulting in lower ion temperatures and neutron rates. However, the discharge was quieter in terms of MHD instabilities and ELM activity. Mark II discharges without gas puffing are discussed in Section 3.

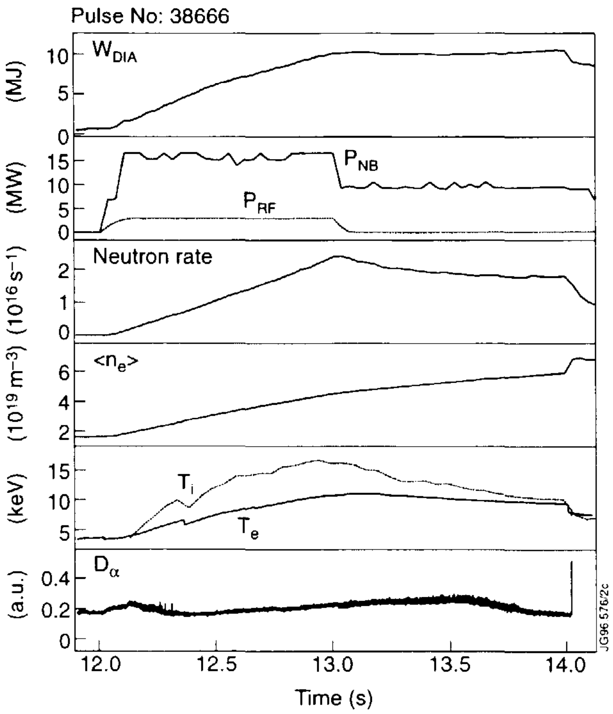

Fig.2: The stored energy from the diamagnetic loop, injected neutral beam and ICRH powers, global neutron rate from fission chambers, volume averaged density from interferometry, central ion and electron temperatures from CXRS and ECE, and D_{alpha} recycling light for power step-down Pulse 38666 in the Mark II divertor configuration.

3. ENERGY AND PARTICLE BALANCE AND COMPONENTS OF POWER LOSS

This section considers the energy and particle balance and components of power loss in these plasmas at both the macroscopic and profile level. The determination of the global confinement time of ELM-free H-modes is determined with more accuracy than previously, since the discharge is in nearly steady conditions for a confinement time, which is not usually the case in this regime. Furthermore, the stored energy hardly changes during the analysis period, and the heating power is nearly equal to the power lost from the plasma by various transport and radiation mechanisms. The assumptions used in extrapolating from a highly dynamic state to a steady-state have a smaller effect on the confinement time calculation. It is also shown that these discharges are able to reach quasi-steady-state conditions because the plasma loss power and energy confinement times vary within restricted limits both before and after power step-down.

Global scaling laws for confinement times in the ELM-free H-mode regime, derived on the basis of transient discharges (dW/dt / P < 0.3 and no hot-ion conditions), are investigated for their validity in quasi-steady-state regimes. The experimentally measured confinement time $\tau_{E,MEAS}$ for the total plasma energy W_{DIA}, and $\tau_{THERMAL,MEAS}$ for the thermal plasma energy W_{THERM}, with the difference being the fast ion energy W_{FAST}, are obtained as follows:

$$\tau_{E,MEAS} \equiv W_{DIA} / P_{LOSS} \tag{1}$$

$$\tau_{THERMAL,MEAS} \equiv W_{THERM} / P_{LOSS} \tag{2}$$

where P_{LOSS}, the power lost from the plasma, is composed of conduction, convection, charge exchange, impurity radiation, and several other processes. The value of this "loss power" is inferred in the usual way from the absorbed neutral beam power P_{ABS} (the difference of the total injected beam power P_{NB} and the shinethrough power P_{SHINE}), the ICRF power P_{RF}, the ohmic power P_{OH} and the time rate of change of the stored plasma energy dW/dt as follows:

$$P_{LOSS} \equiv P_{ABS} + P_{RF} + P_{OH} - dW/dt \tag{3}$$

During high power beam heating in these discharges, the ohmic heating term is negligible. In what follows, only beam heated discharges are considered, so $P_{RF}=0$. The ELM-free H-mode scaling laws [16] for predicting the confinement times for total plasma energy and the thermal energy (the thermal energy law is referred to as ITERH93-P) are:

$$\tau_{ELM\text{-}FREE,TOTAL} \equiv 0.045\ I_p^{0.87}\ B^{0.45}\ P^{-0.55}\ M^{0.43}\ R^{1.84}\ n^{0.03}\ \varepsilon^{-0.02}\ \kappa^{0.53} \tag{4}$$

$$\tau_{ELM\text{-}FREE,THERMAL} \equiv 0.036\ I_p^{1.06}\ B^{0.32}\ P^{-0.67}\ M^{0.41}\ R^{1.79}\ n^{0.17}\ \varepsilon^{-0.11}\ \kappa^{0.66} \tag{5}$$

The quantities are plasma current Ip in MA, vacuum toroidal field B at the magnetic axis in T, plasma loss power P in MW (taken as P_{LOSS} from eq. (3) as was used in deriving the scaling laws from the data base), mass M (taken as 2.0 for deuterium), major radius R of plasma geometric axis in m, line-average electron density in units of $10^{19}m^{-3}$, inverse aspect ratio ε, and elongation κ. In Eq. (5), the loss power used in the database derivation of the scaling law also included bad orbit losses and charge exchange losses of beam particles. Bad orbit losses are completely negligible, and beam charge exchange losses are typically less than 1 MW and decreasing after the first 0.5 s of heating, so these terms are not used in the calculation of P here. The quantities used in this calculation are smoothed with a Gaussian of 235 ms FWHM (Full Width Half Maximum), which contributes to the height and time width of discontinuities observed at power step-down or rapid changes in plasma conditions. The typical uncertainty for the predictions from these scaling laws is expected to be in the range of 10%-20%, given the scatter in the database used to derive these laws.

Power step-down at different levels of plasma stored energy provides insight into the behaviour of the plasma loss power and its scaling. In the Mark II configuration, discharges with long periods free of any instabilities, at 2.8 MA and 2.8 T, for Pulses 38100, 38102, 38104, each had different step-down timing. Fig.3 displays the stored energy from the diamagnetic loop, injected neutral beam power, absorbed heating power, plasma loss power, energy confinement time of the total stored plasma energy and the confinement time predicted from the ELM-free H-mode total energy scaling law, D_{alpha} recycling light, and edge MHD activity. Power loss by beam shinethrough is as large as 5 MW at the low initial densities, and the absorbed heating power is several MW less than the injected beam power during the first few 100 ms while the density is rising. The loss power is therefore initially considerably smaller than the absorbed power during this phase. The radiation loss power is small at about the 1 MW level. In the absence of gas puffing during the ELM-free phase, low recycling in the Mark II divertor allows a rate of density rise in the plasma equal to the absorbed neutral beam particle rate.

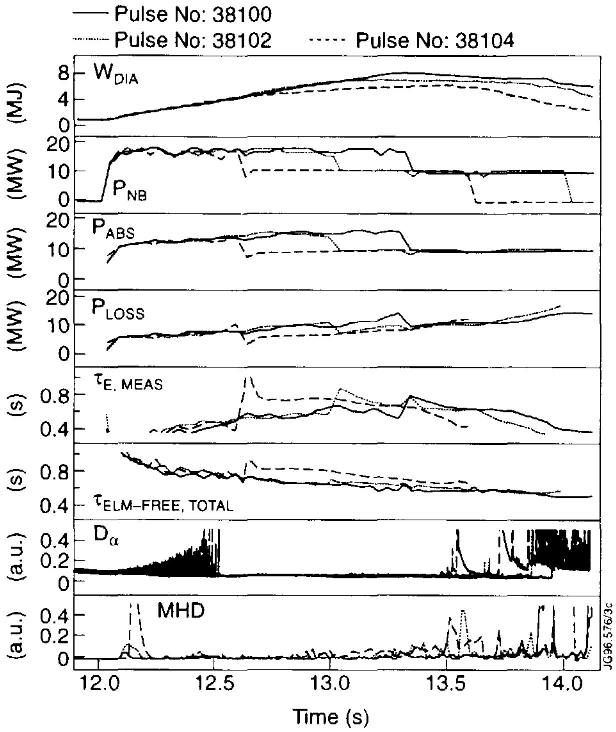

Fig.3: Stored energy from the diamagnetic loop, injected neutral beam power, absorbed heating power, plasma loss power, energy confinement time and confinement time from ELM-free H-mode total energy scaling law, D_{alpha} recycling light, and edge MHD activity for power step-down Pulses 38100, 38102, 38104 with different step-down times in the Mark II divertor configuration.

A suitable time interval for energy confinement analysis is 12.5-13.5 s, when the levels of recycling light and instability are very low. As a result, all the discharges have similar energy confinement times of about 0.6-0.8 s, the same range as predicted from ELM-free H-mode total energy scaling, and each discharge's confinement time is in approximate agreement with its own scaling prediction. The experimentally measured confinement time tends to increase after the power step-down occurs, from a level 10-20% below the scaling prediction to a level 10-20% above it. These error levels correspond to the errors in fitting the scaling law to the data base. Before 12.5 s, the discharges are subject to ELMs, and the scaling laws, not necessarily applicable in conditions with transition ELMs, predict considerable higher confinement times than are actually observed. Near the end of the quiescent interval, all discharges are tending towards a stored energy of about 7 MJ at an injected heating power (about equal to the absorbed power) after step-down of about 10 MW. The loss powers vary from 6-10 MW during this quiescent phase.

The level of total plasma plus shinethrough power loss is important, since the maximum stored energy achievable in high performance discharges is roughly determined by the product of the heating power above this total level ($P_{NB}+P_{RF}+P_{OH} - P_{LOSS} - P_{SHINE} = dW/dt$) and the length of the ELM-free period. Figure 4 illustrates that for the high current (3.5 MA) and toroidal field (3.4 T) Pulse 34236, the total of the plasma plus shinethrough power loss remains in the range 8-12 MW throughout the ELM-free period. This total results from a shinethrough power loss which is decreasing, and a plasma loss power which increases as a function of time. The plasma total energy confinement time improves significantly from ~0.8 s before step-down to ~1.2 s after, as compared to a predicted confinement time of ~1.0 s based on ELM-free H-mode total energy scaling. As above, the measured confinement times are within the 20% error bars of the scaling laws, but the confinement improvement from before the step-down to after it is clearly real, and outside of measurement errors. The fast ion stored energy after step-down is considerably less than 1 MJ, hence the measured confinement times and scaling law predictions based upon plasma thermal energy rather than total energy are nearly identical, as seen in Fig.4.

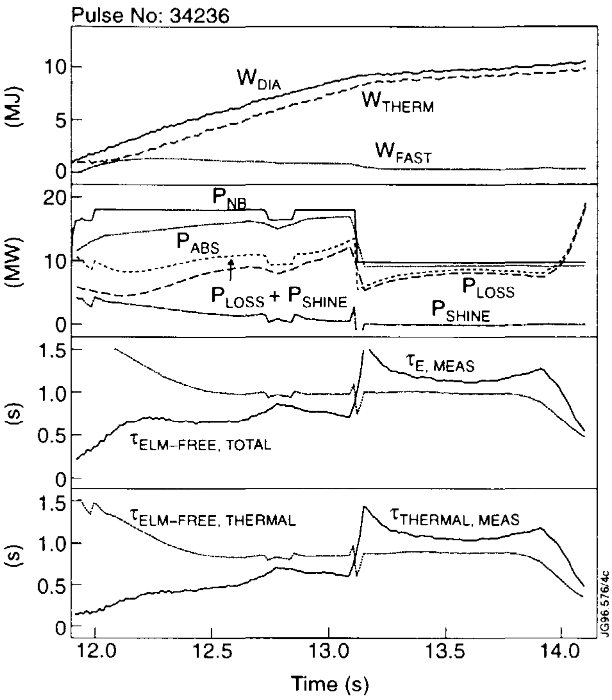

Fig.4: The stored total, thermal and fast ion energy, injected and absorbed neutral beam power, plasma loss power and shinethrough loss power and their total, measured energy confinement times and confinement times from ELM-free H-mode total energy and ITERH93-P thermal energy scaling laws, for power step-down Pulse 34236 in the Mark I divertor configuration.

It may also be noted that similar behaviour is observed in the transient discharge Pulse 33643 during the first second of beam heating, with the experimentally measured time rising to, and the scaling law confinement time falling to 1.0 s, after 1.0 s of beam heating. However, after this time, the confinement times rapidly degrade in the presence of continued full power heating.

It may therefore be concluded that the experimentally deduced confinement times of quiescent quasi-steady discharges are comparable to or even better than those inferred from transient conditions, over the ranges of 2.8-3.4 T and 2.8-3.8 MA (see also Pulse 33106 in Section 6), and are 10-25% higher than the ELM-free scaling laws for either total energy or ITERH93-P thermal energy confinement time.

A TRANSP code simulation [17] of the profile evolution of step-down Pulse 34236 illustrates that the elimination of the transient terms makes it possible to more clearly investigate the power balance, since the dW/dt term in the ion power balance becomes negligible after step-down. Experimentally measured kinetic quantities such as profiles of densities and temperatures are input to TRANSP, and the code verifies these measurements by calculating global quantities such as the stored energy and neutron emission shown in Fig.1. These parameters were simulated to within a few percent, but only after the ion temperature and rotation velocities were reduced by 10% (within error bar limits) and the profile position aligned with other diagnostics by a 0.05 m shift.

Consistency with the measured profile of the neutron yield was also obtained by the simulation. The line integrals of the neutron emission have been routinely measured by the JET neutron profile monitor [18,19]. Figure 5 shows the radial profiles of the calculated line emissivities from TRANSP at 13.7 s compared to the measured line integrals from the 10 channel horizontal neutron profile monitor. The agreement is excellent except for the central channel, which is slightly more peaked in the measurements. The calculation is even so consistent within the 10% channel to channel measurement error. Due to the upshifted plasma, with the axis intersected by channel 4, channels 1-7 view approximately the central half of the plasma, and channels 8-10 view outside this region, where the neutron emissivity is observed to be relatively low.

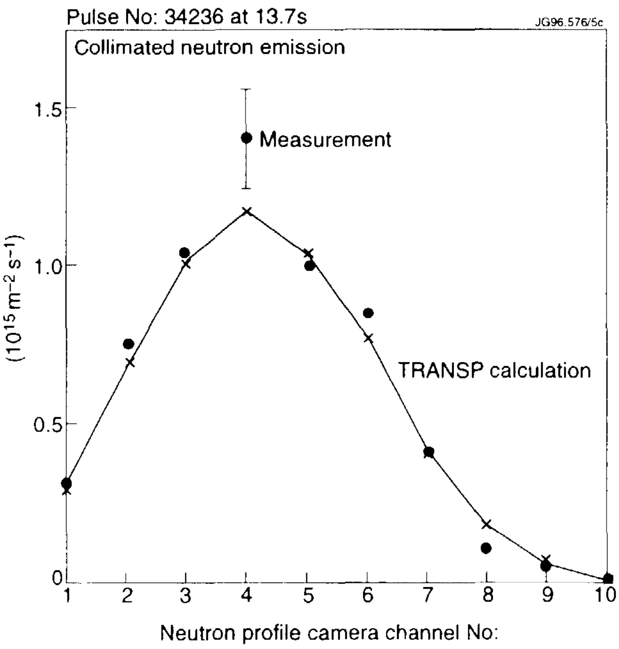

Fig.5: The radial profiles of the calculated line emissivities from TRANSP at 13.7 s are compared to the measured line integrals from the 10 channel horizontal camera of the JET neutron profile monitor.

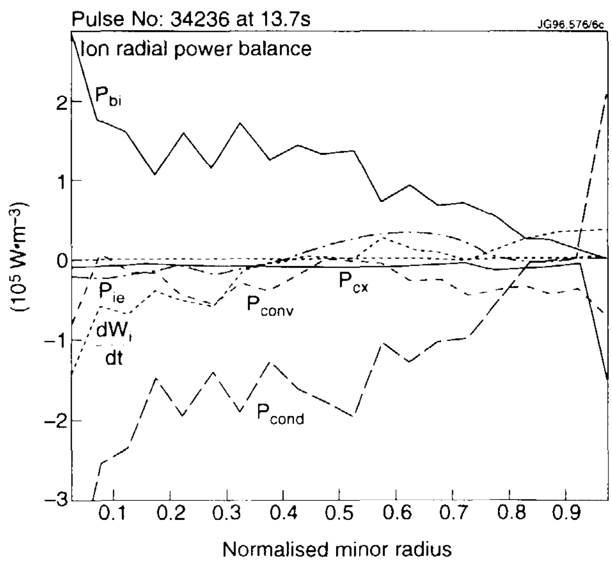

Fig.6: The radial profile of the ion power balance, including heating from beam ions and power loss from conduction, convection, ion-electron transfer, charge exchange and the time derivative of the ion stored energy, is shown for a simulation of Pulse 34236 at 13.7 s.

In Fig.6, the radial power profile between r/a of 0.1 and 0.9 of the ions is shown for a simulation of Pulse 34236 at 13.7 s. The thermal ion power balance in the core is dominated by the beam heating versus ion conduction losses. Since the ion and electron temperature difference is relatively small at this time, so is the transfer power. The ion thermal conductivity within the inner half of the minor radius ranges between 0.3-0.7 m^2/s, a few times the neo-classical value of 0.08-0.18 m^2/s. Separate analysis of transient ELM-free discharges has shown that core transport is characterised by ion neoclassical thermal conductivity plus a combination of Bohm and Gyro-Bohm terms [20].

4. NEUTRON EMISSION SOURCES AND FUSION POWER PRODUCTION

In this section, the neutron emission sources are determined by direct observation and code simulation. If beam-thermal fusion had dominated the neutron emission, then removal of the beams during step-down would have also eliminated most of the neutron production rate. That in fact the fusion power remains mostly unchanged, even when eliminating a large fraction of the beam heating power, is evidence that thermal fusion is the largest contributor to neutron production in step-down discharges. During the quiescent period after step-down, the thermal ion pressure and hence the neutron production rate changes more slowly than the ion temperature due to the rising density. The fusion reactivity scales as $n_i^2T_i^2$ at 17 keV for D-D and 14 keV for D-T thermal fusion, and hence as the square of the ion pressure. The ion temperature stays above this during the quiescent period. At lower temperatures, the reactivity per ion falls faster than T_i^2 (e.g. as $T_i^{2.5}$ at 9 keV in D-D and 10 keV in D-T).

To illustrate quantitatively the contributions to neutron production, Fig.7 shows the calculated time-dependent contributions of beam-beam, beam-thermal and thermal fusion to the neutron rate and their total as calculated by the TRANSP simulation for Pulse 34236, which is seen to agree well with the fission chamber measurements of the total neutron production rate. Over 60% of the neutrons result from thermal fusion. At step-down, when most of the high current 80 keV PINIs are turned off, the decrease in their beam-thermal contribution approximately equals the decrease of the global yield.

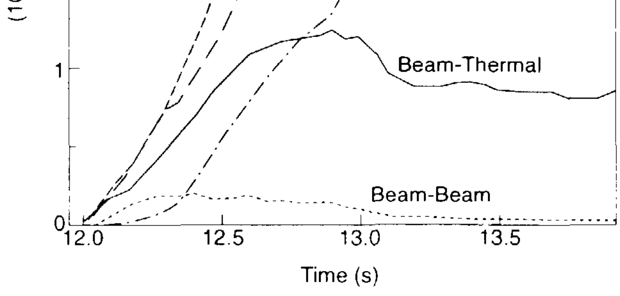

Fig.7: The time dependent contributions of beam-beam, beam-thermal and thermal fusion to the neutron rate calculated by the TRANSP code, their total and the fission chamber measurements of the total neutron production rate for Pulse 34236.

TRANSP calculates expected fusion power and alpha heating contributions by substituting tritium beams for high energy deuterium beams. In the step-down phase of a D-T simulation of Pulse 34236, 9.3 MW of beam heating after step-down produces a quasi-steady fusion power decreasing very slowly from about 7 MW, of which 2/3 results from thermal fusion. With the assumption that alpha power could be substituted for beam power, the heating power minus the alpha power of 1.4 MW equals 7.9 MW, which nearly equals the plasma loss power (allowing for the slow rise in plasma energy), hence giving a fusion Q approaching 1. The ratio of the predicted D-T neutron rate in the simulation to the measured D-D neutron rate in the actual discharge is 84 in the middle of the quiescent phase, compared to the value of 88 expected from simple ratio methods for JET [12].

In the absence of alpha heating, the electron stored energy increases by about 1 MJ over the nearly 1 s after step-down, starting at about 3 MJ. The electron temperature changes little due to the density increase. With alpha heating included, Fig.8 portrays the radial profile of the electron power balance at 13.7 s during quasi-steady-state conditions. Core alpha heating is larger than ion-electron transfer and beam heating. The alpha heating should globally provide over a MW of power to the electrons, which should lead to a measurable increase in the electron energy and temperature.

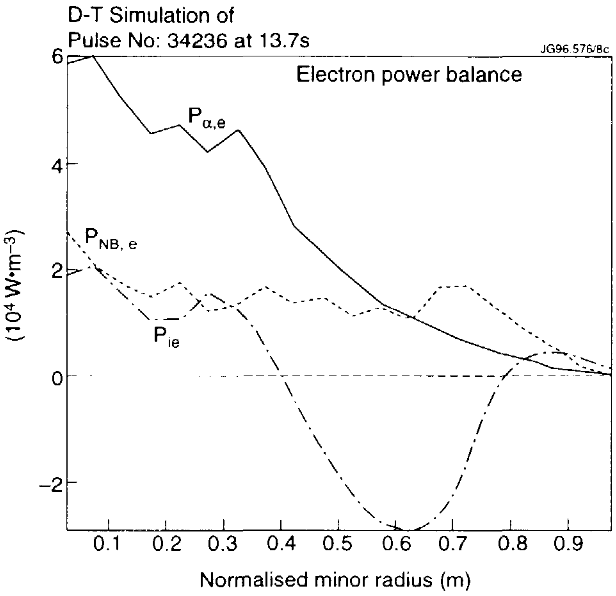

Fig.8: The radial profile of the electron heating by alpha particles, beam ions, and ion-electron transfer is shown for a d-t simulation of Pulse 34236 at 13.7 s.

5. DISCHARGE TERMINATION

The study of instability and termination is complicated in transient discharges by the fact that many relevant parameters are evolving simultaneously, including the pressure gradients and current density profile everywhere in the plasma. Quasi-steady discharges reduce these complicating effects, as follows.

In power step-down discharges, for the one second after the step, the stored energy and neutron rate remain relatively robust against MHD activity and sawteeth. Step-down discharges provide a useful vehicle for the study of termination events, since parameters change very slowly, particularly edge pressure gradients. Nevertheless, step-down discharges still suffer from termination events [1,2]. Figure 3 shows that in Pulse 38100, the stored energy declines slowly, excluding a global pressure limit as a termination cause. Other parameters of Pulse 38100 are shown in Fig.9 on an expanded time scale, from the step-down time at 13.30 s until the terminating event at 13.93 s, a Giant ELM.

Sawtooth crashes do not directly contribute to terminations in these discharges. A sawtooth crash at 13.62 s in Pulse 38100 seen on the ECE measurements of the electron temperature at different major radii from 2.96 m to 3.69 m shows a classic temperature inversion, with the inversion radius halfway between these limits, but with almost no effect on the outermost temperature. The plasma axis and outer boundary are at 3.00 m and 3.86 m. No effect appears on the density line-integral near the edge (at R=3.75 m) or the edge recycling light. Pulse 34236 and Pulse 38666 also exhibit this robustness against sawteeth. In the case of Pulse 38666, the sawtooth occurs just before the terminating event, but does not evidently trigger it, since the electron temperature near the plasma edge is unaffected. The sawtooth temporarily reduces the central electron temperature.

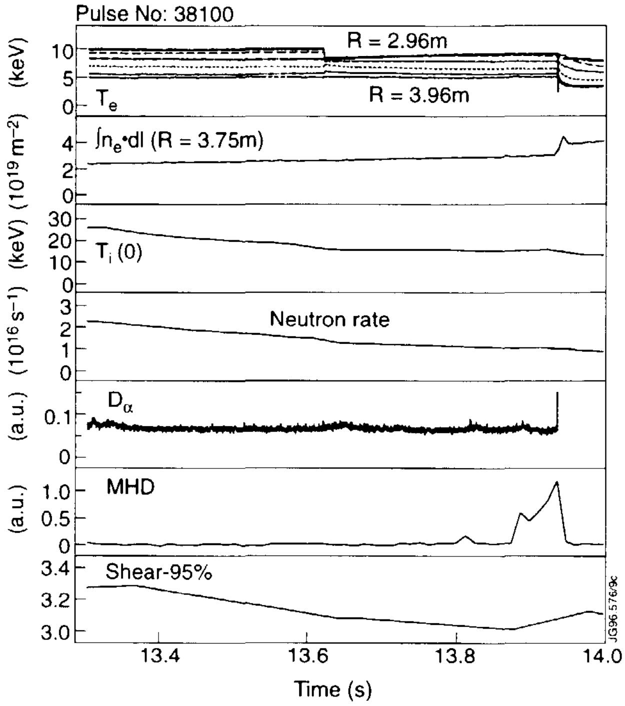

Fig.9: Electron temperature measured at different major radii from the plasma axis to near the outer edge by ECE, the line-integral density measured by an interferometer chord near the plasma edge, the peak ion temperature measured by CXRS, the global neutron yield from fission chambers, the D_{alpha} recycling light, edge MHD activity at 10^4 Hz measured by a comb-filtered magnetic probe, and an MHD equilibrium deduced shear at the 95% flux surface for power step-down Pulse 38100 in the Mark II divertor configuration.

During the step-down phase from 13.3 s to 13.9 s in Pulse 38100, the edge density measured by an interferometer channel increases slowly but the edge electron pressure gradient, measured by LIDAR, and the edge ion pressure gradient, measured by CXRS, remain unchanged. The axial ion temperature and the resultant global neutron production rate decline slowly. The edge recycling light (shown on a sensitive scale) remains constant until a Giant ELM. No precursor activity appears on the recycling light. The plasma current, from the MHD fitting code EFIT, slowly redistributes away from the plasma core, causing a slow decrease in the edge shear as shown in Fig.9. The edge current density and q profile change by a few percent. The only discernible precursor activity appears on a magnetic pickup coil sensitive to the ~10^4 Hz frequency characteristic of the "outer mode" instability and begins about 100 ms before the Giant ELM. This outer mode has been identified [1,2] as a kink instability, in this case apparently triggered by the current profile redistribution. Giant ELMs were the cause of termination in Pulse 34236 and Pulse 38666, and seem to represent the main obstacle to quasi-steady-state discharges.

6. DISCHARGE OPTIMISATION

Even though considerable progress has been achieved in approaching steady-state operation, there are still several obstacles to true steady-state operation, in particular the plasma density increase and plasma instability termination. This section discusses attempts to further optimise the discharges.

Optimisation of hot-ion ELM-free H-mode discharges in JET has been previously discussed [3,15]. The experiments reported here explore the optimum beam energy composition and power wave forms for power step-down.

Experiments were performed to optimise the choice of beam energy, since at JET there are two beam boxes, one at 140 keV, the other at 80 keV maximum energy. There are potential advantages and disadvantages for either choice. At a given level of injected power, higher energy beams have the advantages of higher fusion reactivity (to maintain neutron rate) and lower particle current (to minimise density rise). However, higher beam energy ions also give relatively more heat to electrons during thermalization (thus reducing the proportion of alpha particle heating in D-T), and are more likely to excite Alfvén instabilities [21] (causing beam or plasma energy loss). Pulse 34236, with the best results, used a power step-down that predominantly retained high energy, low current 140 keV beams. Figure 10 illustrates the effects of beam energy with two identical discharges apart from the choice of beam energy after step-down, Pulse 38102 (see also Fig.3) and Pulse 38103. The total beam powers retained after step-down are identical, but mainly composed of 140 keV beams in Pulse 38102 and 80 keV beams in Pulse 38103. The 140 keV beams in Pulse 38102 maintain the stored energy and neutron production rate at a noticeably higher level. Even though the threshold was exceeded for excitation of Alfvén

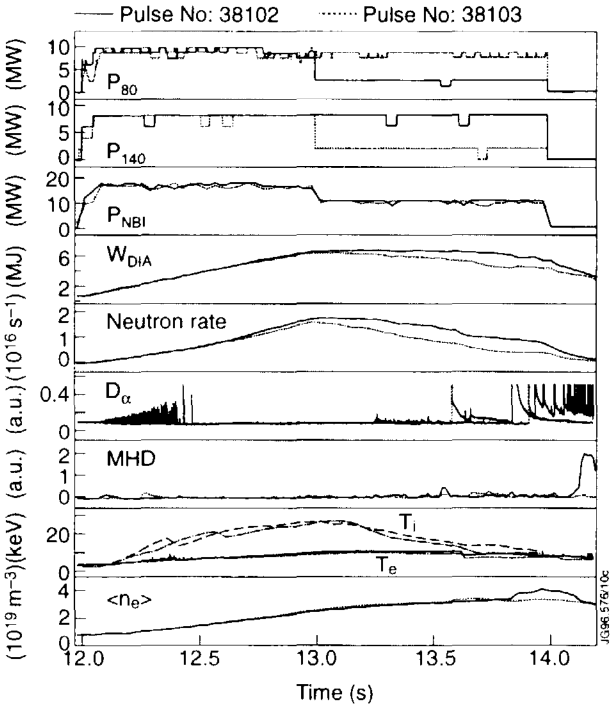

Fig.10: Total injected beam power and the 80 keV and 140 keV contributions, stored energy from the diamagnetic loop, global neutron rate from fission chambers, the D_{alpha} recycling light and edge MHD activity at 10^4 Hz measured by a comb-filtered magnetic probe for power step-down Pulses 38102 and 38103 in the Mark II divertor configuration.

instability [21] by the 140 keV beams in 38102, there was no evidence of any deleterious effect or of Alfvén wave excitation in excess of that in 38102. The central ion and electron temperatures are slightly higher, and the density rise is slower in Pulse 38102, with a beam fuelling rate about 20% lower. The MHD and recycling light levels remain small for both discharges. There is a small amount of recycling light activity from 13.3 to 13.6 s in the 80 keV beam Pulse 38103, with an ELM occurring at 13.6 s, whereas an ELM occurs at 13.8 s in Pulse 38102. Sawteeth occur in the core of both discharges soon after this time, but have little effect on the subsequent discharge evolution.

The plasma density rise influences the optimisation of the beam power wave form. To minimise the density rise, the initial heating power should be as high as possible to considerably exceed the total of the shinethrough and plasma loss, until the plasma stored energy nearly reaches the limit imposed by instabilities [1,2], followed by a step-down to (relatively low current) 140 keV beams. Initial heating at a lower level for a longer time is not advantageous. Density builds up as the product of trapped beam current and time, but energy builds up as the product of (trapped beam power minus total loss power) and time. Particle density is in fact lost by convection, but in these discharges the particle confinement time is usually much longer than the energy confinement time. Therefore, a longer build-up time produces a higher plasma density at a given stored energy; making it more difficult to achieve the hot-ion regime.

In one step-down discharge (Pulse 36992) maintained mostly by 80 keV beams, the electron density did become constant for 1 s during ELM-free H-mode conditions, but with a high radiative power loss and a poor energy confinement time, in far from ideal conditions.

It can be advantageous to step-down the power at relatively high performance, and to heat at a level somewhat above the loss power. In the first high-performance step-down Pulse 26064 from the "PTE" series of experiments [11], the applied power was reduced to 11 MW after 1 s of heating at 15 MW, and the plasma stored energy continued to slowly increase during the next second to nearly 11 MJ, accompanied by a slowly rising neutron rate, in the presence of a loss power of 8 MW. The plasma current and toroidal field were 3.1 MA and 2.8 T, produced in a divertor configuration (before Mark I installation) with a large plasma volume of 100 m^3.

To preserve a high energy content, H-mode conditions need to be maintained, which might be expected to constrain the minimum values of the heating power waveform. Studies [22,23] show that a total heating power of 7-9 MW is needed to produce an L-H mode transition for 3 MA, 3 T plasmas at densities 2-5 $\times 10^{19} m^{-3}$. The reverse transition can occur at a lower power than the L-H transition in ELM-free H-modes (although not in ELMy H-modes) [24]. Figure 11 illustrates the results of a step-down from 16.4 MW to 4.5 MW for Pulse 33106 at 3 T, 3.8 MA. After step-down, the stored energy falls very slowly for 0.5 s while the plasma remains ELM-free. There are some weak MHD events accompanied by small recycling light increases at 14.87 s and 14.99 s. The plasma total loss power of 6 MW, compared to the beam power of 4.5 MW (and negligible Ohmic heating), remains well below the L-H transition

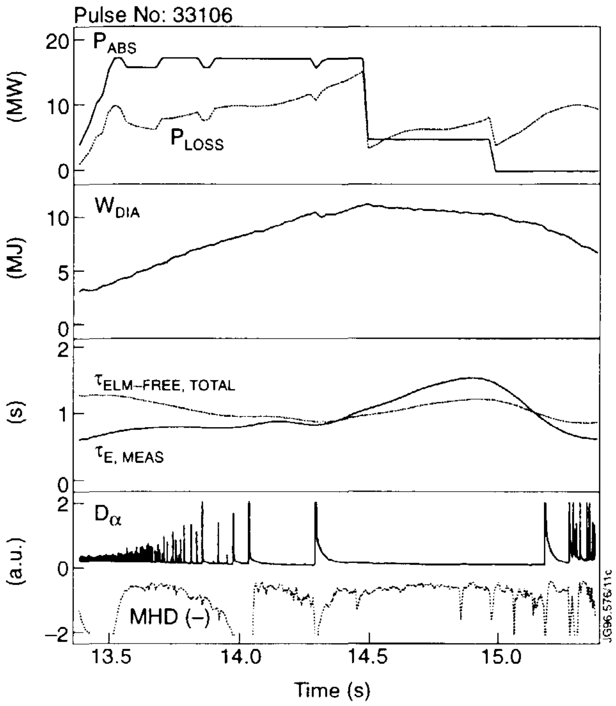

Fig.11: Absorbed neutral beam power, plasma loss power, stored energy from the diamagnetic loop, total energy confinement time and confinement time from the ELM-free H-mode total energy scaling law, D_{alpha} recycling light and (negative of) MHD edge activity for power step-down Pulse 33106 in the Mark I divertor configuration.

power calculated to be about 10 MW at a density of about 6×10^{19} m^{-3}, but the plasma stays in H-mode. There would therefore seem to be a hysteresis in the transition power. The energy confinement time reaches 1.5 s during the instability free period and is 25% above the expected scaling law time of 1.2 s. Shinethrough corrections are negligible at the high density. Because the loss power is sustained by the decay of the plasma stored energy after beam heating stops, the plasma remains ELM-free for an additional 0.2 s before a Giant ELM causes a termination, although minor events occur at 15.08 s and 15.16 s.

In addition to demonstrating that plasmas can be maintained in the H-mode with relatively low loss power, either the low beam power or the zero beam power regimes may prove suitable for alpha heating studies in D-T plasmas. The power balance would be less dominated by beam heating, but more dominated by energy time derivative terms, than a quasi-steady step-down discharge.

7. CONCLUSIONS

The power step-down method in JET produces quasi-steady, high performance plasmas. It has been demonstrated that the high stored energy and high neutron production rate characteristic of the normally transient, hot-ion ELM-free H-mode regime can be maintained in a quasi-steady condition. The discharge quiescent period is comparable to or longer than the relevant plasma time-scales. These discharges provide the unique opportunity for comparing energy confinement time measurements with ELM-free scaling laws, mostly derived on the basis of transient discharges, for a time as long or longer than the energy confinement time.

An analysis of the macroscopic energy and particle balance and components of power loss in these plasmas has shown that the total shinethrough plus plasma loss power varies within relatively restricted limits (typically 8-12 MW) both before and after power step-down, so these discharges enter a quasi-steady condition by a power step-down to the loss power level. During the first second of high power heating, this power is the sum of decreasing losses from beam shinethrough and increasing plasma loss power. When the heating power is stepped down in the discharge with the highest neutron production rate, the plasma energy confinement time of 1 s and stored energy of 10 MJ are maintained (self-consistently) in quasi steady-state by a heating power of about 10 MW. An analysis shows that this loss power behaviour conforms to the parametric dependence of the ELM-free H-mode confinement time scaling law, although experimental confinement times are at or somewhat below the scaling law in the transient phase, and 10-25% above it in the quasi-steady phase. An increase in confinement time is apparently observed from before the stepdown to after it, but it is not obvious whether this is due to some fundamental change in confinement, or whether it is a transition from a less accurate to a more accurate regime for calculating confinement. Since dW/dt reaches a nearly constant level both before and after stepdown, although at very different levels, the confinement improvement would seem to be real. In a TRANSP simulation of the profile evolution of a step-down discharge, the elimination of the transient terms makes it possible to demonstrate that the thermal ion power balance in the core is dominated by beam heating and ion conduction losses, and that ion thermal conduction is a few times neoclassical.

An examination of the neutron emission sources has shown that the discharges after step-down are dominated (>60%) by thermal fusion, and that the neutron production rate is not greatly diminished by eliminating a large fraction of the beam heating power. In extrapolation to D-T operation, it should be possible to produce conditions in which the total fusion power is comparable to the discharge heating (or the equal loss) power. The alpha particle power would become the largest term in the electron power balance.

Quasi-steady operation has allowed a more careful investigation of the evolution towards discharge termination. In particular, the constant edge pressure gradient contributes to the improved stability of these discharges. The terminating Giant ELM usually observed seems to be the result of a slowly evolving current density profile that reduces the edge shear and also triggers an outer mode instability identified as a kink mode.

Several topics have been investigated in the process of optimising the approach to steady operation. It has been shown that at equal power levels, the choice of 140 keV, in preference to 80 keV beams, to be retained after power step-down gives an improved stored energy and neutron production in the presence of reduced rates of fuelling and density increase, due to lower beam current at high beam energy. Since the plasma density usually increases as fast or faster than the beam fuelling rate, it is advantageous to heat the plasma as rapidly as possible to the desired level of stored energy, usually just below instability thresholds, and then step-down to low particle current, high energy heating beams. In the experiments studied so far, the plasma has tended to remain in H-mode even when the step-down power is relatively low compared to the expected L-H transition threshold.

In summary, it has been shown that the power step-down method has provided a significant advance towards the regime of steady-state high performance.

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