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HIGH FUSION POWER STEADY-STATE OPERATION IN JET D-T PLASMAS

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ABSTRACT. Because of its large size, single null divertor, and flexible magnetic geometry, JET is capable of producing the most reactor-relevant plasmas of any present generation tokamak. In the recent deuterium-tritium experiments the fusion performance of these plasmas was tested for the first time. Over 4 MW of fusion power was produced in a high power, steady state pulse of 5 s, limited by the duration of the heating power. The fusion Q^E, defined simply as the fusion energy produced divided by the input energy over this 5 s interval, was 0.18. The performance of our DT ELMy H-mode discharges extrapolates to ignition in ITER and thus provides increased confidence in its current design. Operation at low q_{95} is possible in JET with no degradation in confinement and provides an improved margin to ignition when extrapolated to ITER.

1. INTRODUCTION

The ELMy H-mode is currently the highest performance mode of tokamak operation which has been demonstrated to be compatible with steady state or long pulse operation [1]. As such, it is the preferred mode of operation for a reactor. One of the goals of the JET deuterium-tritium experiment, DTE1, was to demonstrate the maximum fusion performance of ELMy H-modes, and thus of steady state operation, possible in JET.

The maximum fusion performance in JET and likely in any next step device is found at the maximum plasma current compatible with diverted operation. In JET, with the Mark IIA divertor installed, this maximum current is 5 MA. In Fig. 1 the total and the thermal fusion Q for the DTE1 ELMy H-mode pulses with a D-T mix of approximately 50:50 are plotted against plasma current. The thermal Q's are calculated using the TRANSP code [2] but normalised to match the total Q deduced from the neutron measurements. Since all but one of these pulses were run with the same value of q_{95}, this plot can be taken as a dependence on either toroidal field or plasma current.

The total fusion Q is dominated by beam-plasma reactions in all but the highest current pulses. The beam-plasma yield, Q_{b-th}, depends primarily on the
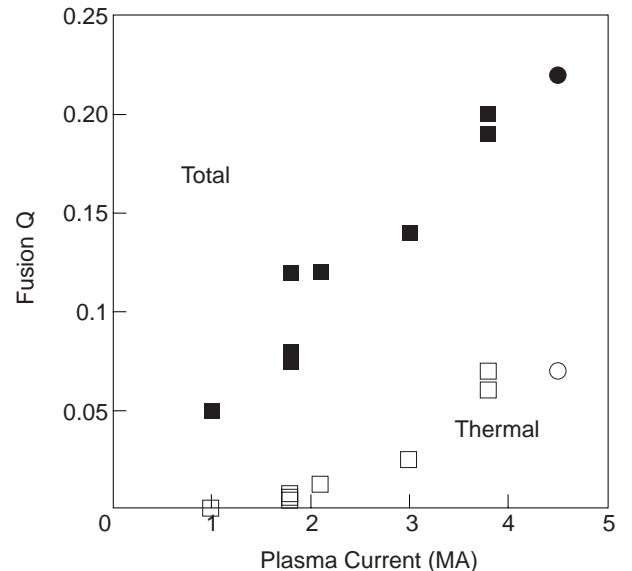
FIG. 1. The total (closed points) and thermal (open points) fusion Q versus plasma current for all of the ELMy H-modes in DTE1 which were run with ≈50:50 D:T mixtures. All of the pulses had $q_{95} = 3.3$ except for the discharge marked with the circles which had $q_{95} = 2.5$.

fast ion slowing down time, τ_s:

$$Q_{b-th} \propto \tau_s \propto \frac{\hat{T}^{3/2}}{Z_{eff}^2 \hat{n}} \tag{1}$$

where $\hat{T}$ is the central electron temperature, $\hat{n}$ is the central electron density, and Z_{eff} is the effective charge of the plasma. The thermal yield, on the other hand, scales strongly with plasma current due
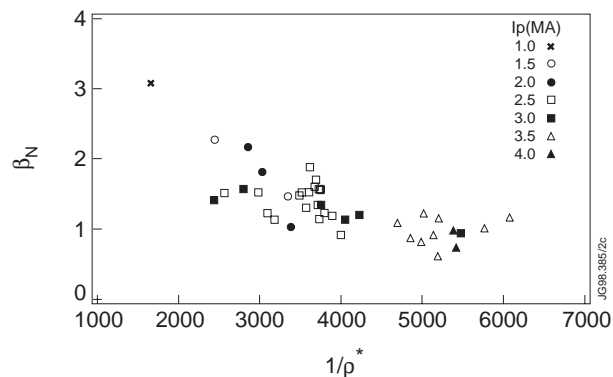
FIG. 2. The normalised β of deuterium steady state ELMy H-modes in JET versus the inverse of the normalised Larmor radius. The data have been selected to have the ITER collisionality $(1.5 \times 10^{-3} < \nu^* < 2.5 \times 10^{-3})$.

to the strong dependence of the confinement on the plasma current and to the almost T^3 dependence of the fusion cross section in the range of operation of these pulses.

The scaling of plasma confinement with dimensionless parameters is a well established technique for predicting the confinement of future machines [3–6]. Indeed, one of the main goals of the DTE1 was to establish the mass dependence of the confinement in such a scaling exercise. The results of these experiments are reported in [7]. For the purposes of this paper, we note that, due to the limited input power available on JET, there is a limiting β which can be obtained at a given normalised Larmor radius, ρ^*. The trade off between β and ρ^* is shown in Fig. 2 for our deuterium steady state ELMy H-mode database. Thus, while it would be preferable to simultaneously match the β and the plasma collisionality, ν^*, required for ITER while at the same time minimising ρ^*, this is not possible in JET. Since the one dimensionless parameter which must be extrapolated from present day machines to ITER is the normalised scale size, it is useful to have data as close as possible to ITER even at the price of reduced plasma β. In this sense the high current data provides plasmas which are as close as possible in present day machines to a reactor plasma.

Until 1997, the toroidal field in JET was limited to 3.45 T. In 1998, following a review of the forces on the TF coils [8] and an upgrade of the relevant power supplies, operation up to 3.8 T in a restricted range of plasma currents and configurations was approved. It was thus possible to operate during DTE1 at up to 5 MA with the old 3.45 T limit and up to 4.2 MA with toroidal fields up to 3.8 T.

Three different magnetic configurations were tested in deuterium for performance at high current. The standard configuration with the divertor strike points on the horizontal target cannot be used above 4 MA due to the potential forces on the vacuum vessel following disruptions. An alternative configuration was therefore developed for use at and above 4 MA. The difference between the two configurations is small. No difference in plasma confinement or performance was found between these two configurations and during DTE1 the standard configuration was used below 4 MA and the high current configuration above.

In addition to these two configurations, a configuration with increased triangularity was also tested. In this configuration, the triangularity at the separatrix was 0.29 as compared to 0.22 in the other two configurations. This is to be compared to the triangularity of the ITER reference design which is quoted as 0.24 at the 95% flux surface and is 0.34 at the separatrix. Due to forces on the vacuum vessel and to out-of-plane forces on the toroidal field coils, this high triangularity configuration is limited to currents at or below 4.0 MA. In the high triangularity discharges, the steady state density obtained was higher than for the lower triangularity pulses. This result has also been found at lower currents [9] and is potentially a route to higher density operation in a reactor. On the other hand, in JET where the plasma temperature is lower than the optimum for thermal DT fusion, operation at higher density results in a significant decrease in the predicted fusion performance. For this reason it was decided to perform the DTE1 high current ELMy H-mode pulses in one of the two low triangularity configurations, depending on the plasma current required. This has the additional advantage of being the same triangularity as the pulses which were performed in DT for confinement studies [7] and thus our high current pulses can be directly included in that database.

The primary heating scheme for our high current experiments was neutral beam injection. This system was modified for DTE1 so that tritium could be injected from one of the two injection boxes, each comprising eight separate sources. In DT the maximum available input power was, in principle, 24 MW but this is limited to 21-22 MW at long (> 2 s) pulse lengths due to heating of inertially cooled components in the beam lines. While the system is capable of up to 10 s injection at moderate input powers, it is only possible to inject for 5 to 6 s with the full input power required for high performance operation. This is due

to restrictions on the pressure in the duct through which the beam passes on entering the torus. Due to the limits on neutron production in DT operation, this pressure limit was particularly a problem in DTE1, where little or no long pulse duct conditioning was possible.

Ideally one would like 'steady state' experiments to be steady in terms of energy confinement, τ_E, current diffusion skin times, τ_{skin}, and wall equilibration time, τ_{Wall}. After the injection of high power, an L-H transition is followed by a rise of the plasma stored energy and, somewhat more slowly, of the core plasma density. At high current the stored energy and density reach approximately constant values after about 2-3 s of the high power phase. There thus remains typically 2-3 s of operation in steady conditions. This is significantly longer than the typical JET energy confinement times of ≈ 0.5 s, so that these pulses are steady in this respect.

Because our high current discharges operate at quite high temperature ($T_i \approx T_e > 5\text{keV}$), the current skin time is long (see, for example [10]):

$$\tau_{skin} \approx \pi a^2 n r_o \tau_e \qquad (2)$$

where a is the plasma minor radius, n is the plasma density, r_o is the classical electron radius, and τ_e is the electron collision time. For typical values of high performance, high current pulses in JET, $a \approx 1$ m, $n \approx 6 \times 10^{19}$ m^{-3}, $\tau_e \approx 1 \times 10^{-4}$ s, and the current skin time is ≈ 55 s, much longer than our pulse lengths. Indeed, the internal inductance of our longest high current DT pulse decreased slightly throughout the heating pulse (Fig. 3). The inductance is calculated from the magnetic measurements using the EFIT [11–13] equilibrium reconstruction code or is calculated using a current diffusion model by TRANSP [2]. Tests of very long pulses at lower current have shown, however, that performance in JET ELMy H-modes can be maintained for times comparable to the current diffusion time with no change in confinement [1].

The equilibration time of the plasma with the wall depends on the neutral plus ion flux to the wall. This flux varies by orders of magnitude around the poloidal circumference of the machine. The sum of the neutral atom and deuterium ion flux to the wall is shown in Fig. 4 for a simulation of a moderate current ELMy H-mode [14]. Using the model applied to the JET carbon walls following the preliminary tritium experiment (PTE) [15], one finds that the equilibration time for surfaces in direct contact with the plasma is less than one tenth of a second while surfaces far from the divertor region, which see only low neutral fluxes, can
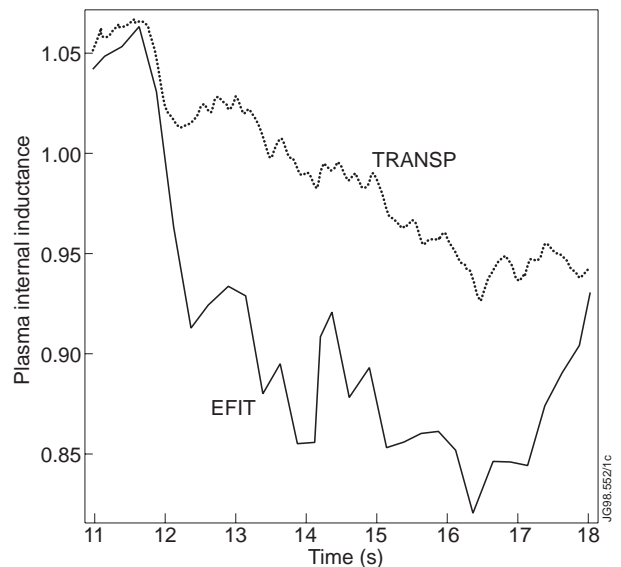

FIG. 3. Time traces of two calculations of the internal inductance of a high power (23 MW), high current (3.8 MA) DT pulse (see text). The heating is applied from 12 to 17 s.

take up to several hundred seconds to reach equilibrium. In the actual experiments, the effect of ELMs complicates this calculation and it may be that the equilibartion time is considerably reduced as compared to that deduced from fluxes measured between ELMs. It is nonetheless likely that surfaces far from the divertor do not reach equilibrium during our five second high power pulses. This results in wall pumping in our long pulse discharges, in which the density tends to decrease gradually during the high power phase despite the central beam particle fuelling.

In summary, the high current DT pulses reported here can only strictly be considered steady state with respect to the energy confinement of the core plasma and not with respect to either the current diffusion time or the wall equilibration or saturation time. Nevertheless, longer pulse experiments at lower currents have shown that the confinement and performance of JET ELMy H-modes does not change even in conditions much closer to being truly steady. We thus expect that the performance of our high current pulses are extrapolable to very long pulse machines such as ITER.

2. FUSION PERFORMANCE

In total three high power, high current pulses were performed during DTE1. Together, the three high performance pulses generated 56 MJ of fusion energy,
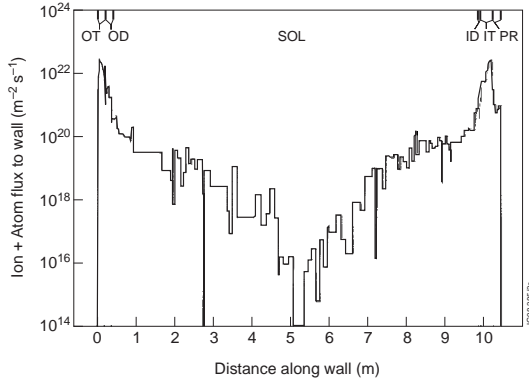
FIG. 4. Simulated flux of hydrogen atoms and ions to vacuum vessel wall as a function of poloidal distance around the machine from the outer divertor target (OT) to the inner target (IT) and the private region (PR). Also shown are the regions of the outer (OD) and inner (ID) divertor trough which are treated as non-wetted surfaces in the simulation. The simulation is for the conditions measured in a moderate current ELMy H-mode discharge between ELMs.
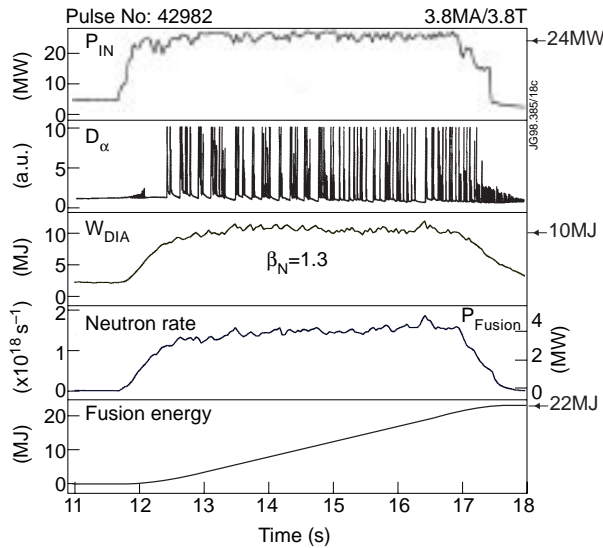

FIG. 5. Time traces of the 3.8 MA, 3.8 T ELMy H-mode which produced a world record 22 MJ of fusion energy.

a significant proportion of the total neutron budget for DTE1, which was equivalent to 700 MJ of fusion energy. The longest duration of these (Pulse 42982) was at 3.8 MA and 3.8 T with 23 MW of heating for 5 s and produced over 22 MJ of fusion energy (Fig. 5).

In this pulse the heating was primarily by neutral beams with 10.5 MW injected as tritium neutrals and 11.0 MW injected as deuterium neutrals. In addition there was 2.3 MW of ICRH heating of a 4% ^{3}He
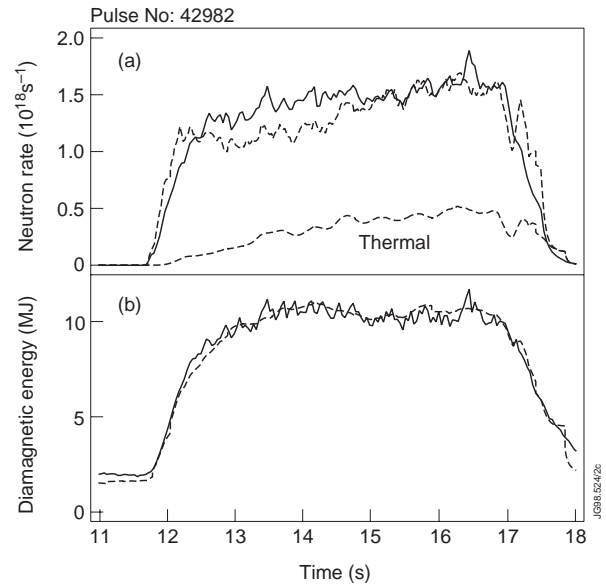

FIG. 6. Time histories of the measured (solid curves) and calculated (dashed curves) (a) total neutron rate and (b) diamagnetic stored energy for Pulse 42982. The calculations are from a TRANSP simulation using the measured temperature and density profiles. Also shown is the TRANSP calculation of the neutron rate due to thermal reactions.

minority. The fusion power produced reached a value of about 4 MW, slightly increasing throughout the pulse due to a slight decrease in the core plasma density and a corresponding increase in the ion temperature. Integrated over the duration of the steady phase of the pulse, the fusion Q^E, defined simply as the fusion energy produced divided by the input energy to the plasma, was 0.18.

The other two high performance DT pulses were a somewhat shorter pulse at 3.8 MA and 3.8 T (Pulse 42762) and a pulse at 4.5 MA and 3.45 T (Pulse 42983) which both had about 3 s of constant, high power heating. The best fusion power (5.3 MW) and Q^E (0.22) were obtained in the highest current pulse as shown in Fig. 1.

The data consistency for all three of our high performance ELMy H-mode pulses has been checked using TRANSP calculations. In Fig. 6, the measured plasma diamagnetic stored energy and neutron rates for Pulse 42982 are compared to those calculated by TRANSP based on kinetic data. Also shown is the neutron rate due to thermal reactions, again as calculated by TRANSP. In this pulse the thermal yield reaches about 30% of the total yield.

The confinement and performance of our high current DT pulses is very similar to that of DD analogues
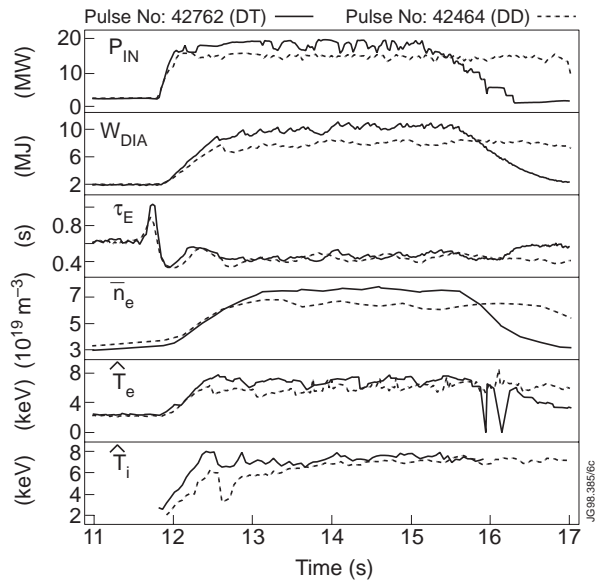
FIG. 7. Time histories comparing two similar pulses, one in deuterium (dashed curves) and one in an approximately 50:50 DT mixture (solid curves).

(Fig. 7). This is consistent with the observation of a very weak mass dependence of confinement made at lower currents [7]. The DT pulses do appear to reach a higher density than their DD counterparts, probably due to the different ELM behaviour [16]. This, as will be discussed below, has a negative impact on fusion performance due to the somewhat lower temperatures achieved in DT for a given input power.

The profiles of electron temperature, ion temperature, electron density and ion density, averaged over the last two seconds of Pulse 42982 are shown in Fig. 8. At these high densities the ion-electron thermal equilibration time is small and the two temperatures are similar as they must be in a reactor. The density profiles are broad which is typical for JET ELMy H-modes. The dilution, which is due primarily to intrinsic carbon and to helium-3 injected as a minority for ICRH heating, is about 35%.

The parameters of our high current pulses can be compared to those expected in ITER. The shape of the JET DTE1 pulses is very similar to what is the reference configuration for ITER. The triangularity of our high current pulses is somewhat lower than the current ITER reference due to restrictions on poloidal field currents and transverse forces on the TF coils (see Section 1). In addition, the safety factor in two of the three high current pulses executed in DT as well as of the majority of the moderate current pulses performed for ρ^*-scaling studies is essentially identical to the ITER reference value. In Table I the dimension-
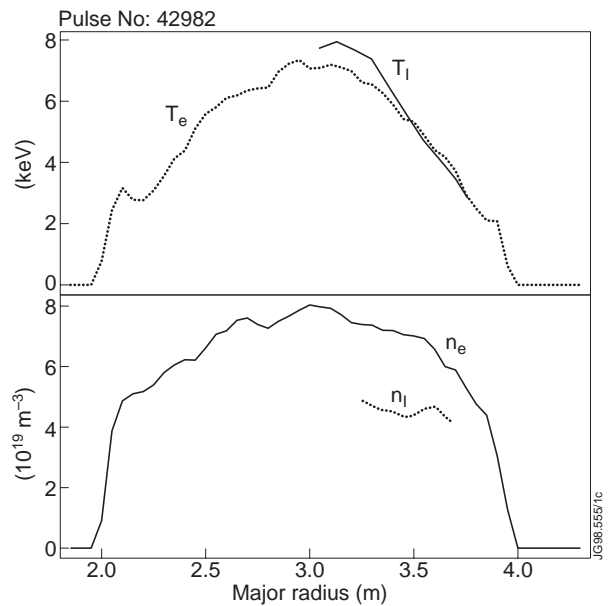

FIG. 8. Profiles as a function of major radius of the electron and hydrogenic ion temperatures and densities for a high power, 3.8 MA, 3.8 T ELMy H-mode pulse in an approximately 50:50 DT mixture.

less variables of two of our high current pulses are compared to those required in ITER and to those of the highest current pulse (2 MA) that attained the normalised β required for ITER. In this way, the trade off between approaching the dimensionless size of ITER and maintaining the required β_N is clear. In our high current pulses the extrapolation to ITER in ρ^* is a factor of 3 at the price of a significantly reduced β_N while at 2 MA, 2 T, where there is sufficient power available to match β_N, the value of ρ^* achieved is a factor 5 greater than that of ITER. The match to the ITER value of ν^* is also better for the higher current pulses.

The Z_{eff} values in Table I are from charge exchange spectroscopy measurements and correspond to roughly a 4% carbon concentration in the plasma centre, 1% beryllium, and 6% helium-3. The one exception is Pulse 42983, which is measured to have a higher central beryllium concentration (7%). The reason for this difference is unclear. These Z_{eff} values are somewhat uncertain. The visible bresstrahlung measurements give higher values (by about 0.5) but are inconsistent with the measured neutron rates. At the end of the operational campaign following DTE1, the transmission of the windows used for the bremsstrahlung measurements was found to be significantly reduced. The Z_{eff} values from visible bremsstrahlung include a correction for this degra-

	JET			ITER
	42756	42982	42983	
R [m]	2.91	2.90	2.89	8.14
a [m]	0.93	0.94	0.96	2.80
B_T [T]	1.95	3.87	3.46	5.68
I_P [MA]	1.99	3.78	4.47	21
q_{95}	3.46	3.51	2.77	3.2
$\tau_{E,th}$ [s]	0.25	0.37	0.51	4-8
ϵ	0.32	0.33	0.33	0.35
δ	0.25	0.23	0.23	0.35
κ	1.77	1.75	1.75	1.73
ρ^*	2.68^{-4}	1.87^{-4}	1.59^{-4}	5.0^{-5}
β_N	2.38	1.25	1.56	2.2
$\beta_{N,th}$	1.97	1.10	1.46	2.2
ν^*	8.2^{-3}	3.1^{-3}	4.2^{-3}	2.0^{-3}
H_{97}	0.95	0.82	0.90	1.0
Z_{eff}	2.5	2.5	2.7	1.8

Table I. Comparison of the parameters of three JET DT pulses with those predicted for ITER.

dation and are thus more uncertain than usual. For these reasons, we prefer the charge exchange measurements, but believe that the uncertainty in the Z_{eff} values to be ±0.5.

It is possible to extrapolate the performance of our high current pulses to what one would expect in ITER either using the fusion yield directly or by scaling in dimensionless parameters along ρ^* while holding β and ν^* constant.

The simplest extrapolation of the fusion yield is the usual $Q \propto \hat{n}\hat{T}\tau$ scaling. This scaling assumes that the DT fusion rate coefficient scales as the square of the plasma ion temperature. In JET ELMy H-modes with predominantly neutral beam heating, the core density is always above a certain minimum value, even with no gas fuelling in addition to the beam particle fuelling. With this minimum density and with the maximum total input power available, it is not possible to obtain steady state discharges which achieve ion temperatures in the range where the fusion rate coefficient scales as T^2, even at high current. In fact, the performance of our high current discharges falls below the simple fusion yield scaling by a factor which is proportional to the ion temperature. Since ITER will operate in the optimum temperature range, it is necessary to include this factor when scaling from JET discharges to ITER. With this correction, one finds that the performance of Pulse

42982, our best 3.8 MA, 3.8 T discharge, scales to ignition in ITER, with little margin.

One can avoid the sensitivity to the correction required for the ion temperature by scaling the stored energy of the JET discharges to ITER and then scaling the ITER performance as W^2, which is equivalent to assuming that any ITER extrapolations are in the temperature region where $\langle\sigma v\rangle \propto T^2$. Extrapolated values based on three JET DT pulses are shown in Table II. In the extrapolation of Pulse 42983, which had $q_{95} = 2.77$, we have assumed that the lower q could be achieved in ITER by operation at higher plasma current, in this case 24 MA as opposed to the 21 MA reference value. We have also implicitly assumed that the Z_{eff} predicted for ITER can be achieved, despite our DT pulses having a somewhat higher value (see Table I). While there was some scatter from day to day, many of the deuterium preparation pulses did have Z_{eff} at or below the ITER value.

At least one word of warning is required when considering such extrapolations at constant β and ν^*. The extrapolated values of density can significantly exceed the Greenwald limit [17]. This is more of a concern for the extrapolation based on the moderate current pulse where the predicted density is 70% above the Greenwald value. The extrapolation from Pulse 42983, because of the higher current assumed, is only 15% above the Greenwald limit, the same margin which is assumed in the ITER reference case.

There being no firmly established theoretical basis for the Greenwald scaling, it is difficult to know whether the extrapolated values represent realistic operating points. The ITER confinement database group has adopted the position of supplementing performance extrapolations at constant collisionality and β with projections where the density is limited to the Greenwald value while the β and confinement enhancement factor are held constant (see, for example, [3]). For the extrapolation of Pulse 42756, this restricted density results in a predicted fusion Q of 26 while the Q deduced based on Pulse 42983 is 151, i.e. essentially ignited. The extrapolation based on Pulse 42982 is below the Greenwald density so no reduction is required.

It can be seen that extrapolations based on a gyroBohm scaling of the confinement predict ignition at the ITER size and field for two of three JET reference pulses. GyroBohm scaling, which is based on the assumption that the size of the turbulence which drives the cross field transport scales with the Larmor radius of the ions, is the scaling which is found

	JET			ITER
	42756	42982	42983	
R [m]	2.91	2.90	2.89	8.14
a [m]	0.93	0.94	0.96	2.80
B_T [T]	1.95	3.87	3.46	5.68
I_P [MA]	1.99	3.78	4.47	21 (24)
q_{95}	3.46	3.51	2.77	3.2
W [MJ]	5.2	10.3	13.8	1100
$\langle n \rangle$ [10^{19}m^{-3}]	5.05	5.95	8.13	9.8
P_{in} [MW]	17.2	23.6	24.5	182
	Predicted ITER Values			
$W_s \propto B^2 a^3$ [MJ]	1204	586	923	
$P_{fusion} \propto W_s^2$ [MW]	1797	426	1056	
P_α [MW]	359	85	211	
$\langle n \rangle_s \propto B^{4/3}/a^{1/3}$ [10^{19}m^{-3}]	14.6	6.9	11.0	
P_{brem} [MW]	224	51	129	
$P_\alpha - P_{brem}$ [MW]	135	34	82	
$P_{required}(gyroBohm) \propto Ba^{1/2}$ [MW]	87	60	69	
$Q(gyroBohm)$	∞	16	∞	
$P_{required}(Bohm) \propto B^{5/3}a^{4/3}$ [MW]	444	192	233	
$Q(Bohm)$	5.8	2.7	7.0	

Table II. Extrapolated values of fusion Q for ITER based on three different JET DT ELMy H-mode pulses. The extrapolations are based on a constant β, constant ν^* scaling. The bremsstrahlung losses are taken as 118 MW for the ITER reference case and assumed to scale as $n^2 T^{1/2} \equiv n^{3/2} W^{1/2}$.

in present day experiments with ELMy H-modes (see, for example [3] and the references therein). The advantange of operating at higher plasma current, even at the expense of reduced q_{95}, is clearly shown in Pulse 42983 which out performs even the moderate current pulse when extrapolated to ITER. Even in the unfavourable Bohm scaling of confinement, which is not seen in present machines, fusion Q's greater than five are obtained in the extrapolations.

3. CONFINEMENT OF HIGH CURRENT DISCHARGES

3.1. Global Confinement

The confinement of pulses from our Mark IIA dataset of steady state ELMy H-modes is compared to that predicted by the 1997 ELMy H-mode scaling law in Fig. 9. In this dataset, pulses which are quasi-steady (averaged over ELM periods) for more than two energy confinement times are included. The dataset includes pulses from a wide variety of divertor magnetic configurations and from all three hydro-

gen isotopes. During the Mark IIA campaign, it has been demonstrated that strong gas fuelling in addition to central fuelling by neutral beams degrades the confinement [9, 18]. In order to restrict the comparison to pulses with good confinement, pulses with gas fuelling in additional to fuelling by neutral beams are not shown in Fig. 9.

It can be seen that the confinement of our higher current discharges falls below the predictions of the scaling law. This is true even of discharges at moderate current ($\approx 3MA$). The difference between the measured and predicted stored energy reaches a maximum of 15-20% at the maximum currents tested.

The dataset shown in Fig. 9 has strong collinearities between the quantities used as independent variables in conventional scaling laws. In particular, the plasma current and toroidal field in our dataset are strongly correlated. The plasma current and density also tend to vary together. Furthermore, this dataset has little or no variation in either plasma size (R) or shape (ϵ, κ) parameters. For this reason we have refitted the data with the exponents of R, ϵ and κ fixed at their values given by the 1997 ELMy H-mode scaling
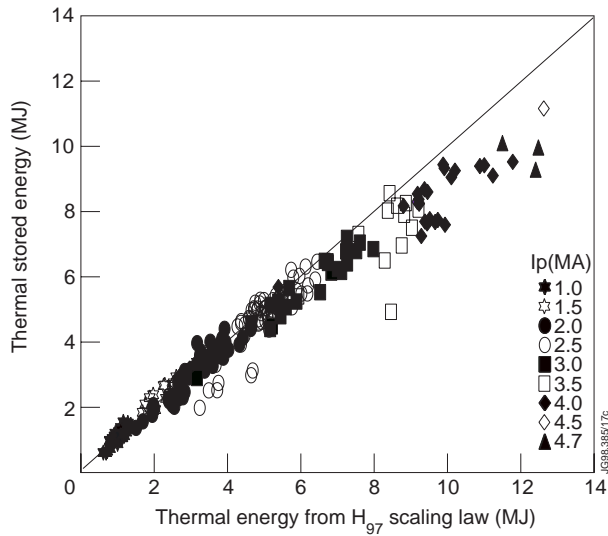
FIG. 9. The stored energy measured for pulses in the JET Mark IIA steady state ELMy H-mode database versus the stored energy predicted by the 1997 ELMy H-modes scaling law. Beam pulses with additional gas fuelling have been excluded from the plot. The data is sorted by plasma current.

law. The resulting fit to our data is:

$$\tau_{th} = 0.030\, I^{0.77}\, B^{0.20}\, P^{-0.67}\, n^{0.42}$$
$$\times R^{2.03}\, \epsilon^{0.19}\, \kappa^{0.92}\, A^{0.24} \tag{3}$$

This fit was also restricted to solutions which satisfy the high-β Kadomtsev constraint [19], as was the 1997 scaling law (ITERH97-P(y)). The fit to our data is very similar to ITERH97-P(y):

$$\tau_{th}^{H97} = 0.029\, I^{0.90}\, B^{0.20}\, P^{-0.66}\, n^{0.40}$$
$$\times R^{2.03}\, \epsilon^{0.19}\, \kappa^{0.92}\, A^{0.2} \tag{4}$$

The biggest difference between the two fits is in the current dependence, which is significantly weaker in the present dataset. The strong correlation between current and field in our data make the separation into the separate exponents uncertain. Tests of fits of subsets of the dataset restricted to one current leave the density and power dependences unchanged within the uncertainties but lead to large variations and large uncertainties in the dependence on the toroidal field. We thus conclude that our data follows the conventional ELMy H-mode scaling but with a weaker dependence on either the plasma current or the toroidal field.

3.2. Edge and Core Confinement

It has become clear from recent experiments studying ELMy H-mode confinement that the confinement may vary independently in the core and the edge plasmas [9, 20]. This has been reinforced by the JET DTE1 results which show that the mass scaling of the core and edge confinement is not only different but scales with opposite signs of the exponents in a power law scaling [7]. As a first step towards understanding the relative degradation of confinement at high current we consider the confinement of the core and edge separately. This is done by measuring the height of the confinement barrier at the plasma edge and ascribing an energy to it given by the product of the pressure at the top of the barrier and the plasma volume, the so-called pedestal energy associated with the confinement barrier.

For a variety of JET ELMy H-mode plasmas, the total thermal stored energy is divided into pedestal and core energy components in Fig. 10. The core or profile energy is taken to be the difference between the total and the pedestal stored energies. Both components of the energy have been normalised to the total thermal energy that one would expect for the discharge based on the 1997 scaling law. The most notable feature in Fig. 10 is the strong mass dependence of the pedestal energy. Nevertheless, the relative degradation of confinement can be seen on both the edge and the profile components of the stored energy. This is in contrast to high density and highly radiative pulses where the majority of the confinement degradation has been shown to be from the pedestal [20]. It is difficult, however, to firmly attribute the degradation, relative to a global scaling law such as H_{97}, to either the core or the edge since the two components may well scale individually in different fashions. In particular, the current dependence one would expect for the stored energy associated with edge confinement barrier has not been established.

3.3. Core mhd Behaviour

The high current DT pulses, which also display a somewhat reduced H-factor (see Table I), have been examined for mhd activity and compared to pulses at lower current. Fig. 11 shows a Fourier spectrum evolution in the high current DT discharge 42983 (4.5 MA, 3.45 T) of mhd activity as measured with a magnetic pick-up coil on the low field side. The display starts just after an ELM and shows three other com-
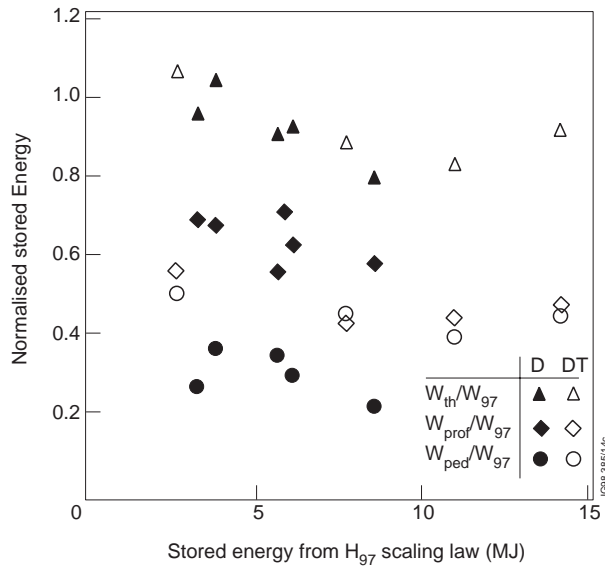
FIG. 10. The total, pedestal and profile thermal stored energy all normalised to the stored energy predicted by the 1997 ELMy H-mode scaling law. The profile energy is simply taken to be the difference of the total and pedestal energies. Solid points indicate pulses in deuterium while open points are DT pulses.
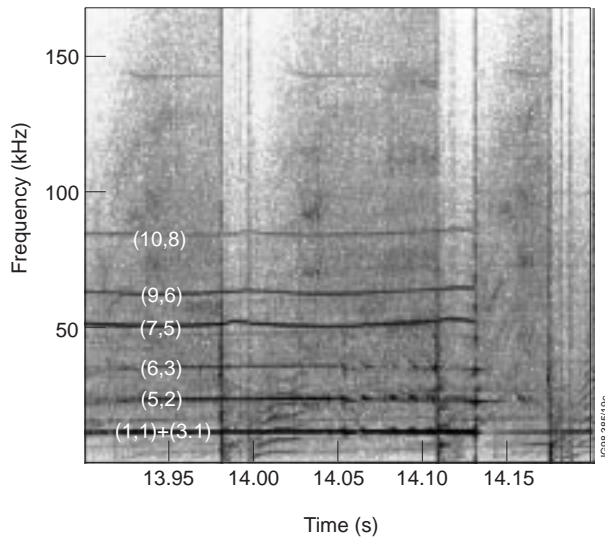

FIG. 11. The Fourier spectrum of mhd activity for a fast time window in a 4.5 MA, 3.45 T DT ELMy H-mode as measured by a magnetic pick-up coil on the low field side of the machine. The numbers in parentheses are the poloidal and toroidal mode numbers of the modes as determined by pick-up coils at different positions around the machine and by fluctuations of electron cyclotron emission from the plasma core.

posite ELMs (at 13.980, 14.107 and 14.172 s) and one sawtooth relaxation (at 14.129 s).

The intensity of the mode activity is spread over

several orders of magnitude with $\delta B_\theta / B_\theta$ varying between 10^{-3} and less than 10^{-7}. The strongest mode is at 11 kHz and has a $(m,n) = (1,1)$ character with (2,1) and (3,1) harmonics at reduced intensity. Other modes located in the core are (5,2), (6,3), (7,5), (9,6) and (10,8) and have smaller amplitudes in the range 10^{-5} to 10^{-6}. The mhd activity that is located in the core of the plasma is not affected by ELMs but all modes located in the core decrease by more than an order of magnitude after the sawtooth collapse.

Also present is a quasi-continuum of modes with high negative (m,n) numbers which rotate in the electron diamagnetic direction in contrast to the discrete modes discussed above. These quasi-continuous modes only occur in H-modes and are strongly affected by ELMs (see the high frequency range in Fig. 11). Both the amplitude and the direction of rotation of these modes is changed after each ELM.

In order to determine if the observed core mhd behaviour could explain the somewhat degraded confinement factors of our high current discharges we have compared Pulse 42983 to another high current discharge (Pulse 42982) and to a lower current shot (Pulse 42756). The main parameters of each of these three DT pulses are given in Table I. They follow the typical trend of somewhat worse confinement factors at high current although Pulse 42983 is better than 42982 in this respect.

Pulse 42983, which has a lower q_{95} than the other two discharges analysed, also has a stronger (1,1) mode. Pulse 42983 has a 20-30 cm magnetic island associated with this mode as compared to the other two, higher q discharges which have similar $\delta B_\theta / B_\theta$ but only 5-8 cm displacements, as measured by electron cyclotron emission profiles. Despite this increased island size, the low q pulse is one of our best high current pulses, suggesting that the (1,1) activity is not responsible for the reduced confinement at high current. This may be understood by examining the amount of thermal energy stored inside the $q = 1$ surface in these discharges. Even in Pulse 42983, where the $q = 1$ surface is at $\rho \approx 0.4$, the fraction of the thermal energy stored by the pressure gradient inside this surface is only 10%.

Apart from the n=1 activity, there is little difference in the core mhd activity of the three pulses analysed. The two lower q discharges have some n=4 activity ((5,4) and other toroidally coupled n=4 modes) which is absent in Pulse 42983. The lowest current pulse, which has the highest H-factor, also has n=3 core modes present at an amplitude of $\delta B_\theta / B_\theta = 3 \times 10^{-4}$ with a measured displacement of

2-4 cm. We thus conclude that, in the small sample of pulses which have been analysed, there is no core mhd activity which is correlated with the relative degradation in confinement observed at high current.

3.4.   Edge mhd Behaviour (ELMs)

In contrast to the core mhd, the edge localised modes (ELMs) do strongly affect the global confinement. Using a simple model for the reheat of the plasma after each ELM [20], one can estimate the confinement of a discharge given the time of the ELMs in the period of interest. In this model, the reheat between ELMs is modelled as an exponential increase of the thermal stored energy on a time scale proportional to the energy confinement time. The confinement is assumed to asymptotically approach some value in the limit of very long periods between ELMs, i.e. low ELM frequency, and to fall to some lower, constant value after each ELM. The constants in the model were determined by analysis of a series of moderate current (2.5 MA), deuterium discharges [20]. These constants have been adjusted using the measured dependence of the global confinement on isotope mass [7] for comparison with our DT pulses but are otherwise maintained fixed for the analysis presented here. The result of this model is a prediction of a modified confinement enhancement factor based on the knowledge of the times of occurrence of the ELMs in the discharge. In this sense, it provides a correction due to ELMs over and above their average influence as included in the global scaling law. In Fig. 12, we compare the confinement enhancement factor deduced from this model with that actually measured for a series of DT ELMy H-mode discharges over a range of plasma currents.

It can be seen that the model reproduces the observed trend in the confinement factors. In particular it can be seen that the rather good confinement (for the high current) seen in the 4.5 MA pulse is due, in large part, to the better edge stability against ELMs. There remains some deviation from the simple model at low confinement factors; the confinement is measured to be even worse than that predicted by this model of the direct influence of the ELMs. This is partly because the core confinement is also degrading in these pulses, as was shown in Fig. 10. It may well be that even this change in core confinement can be related to the ELM behaviour. Several of the core transport models currently being tested by the ITER Confinement Working Group depend strongly on the value of the edge temperature assumed [3]. Thus dis-
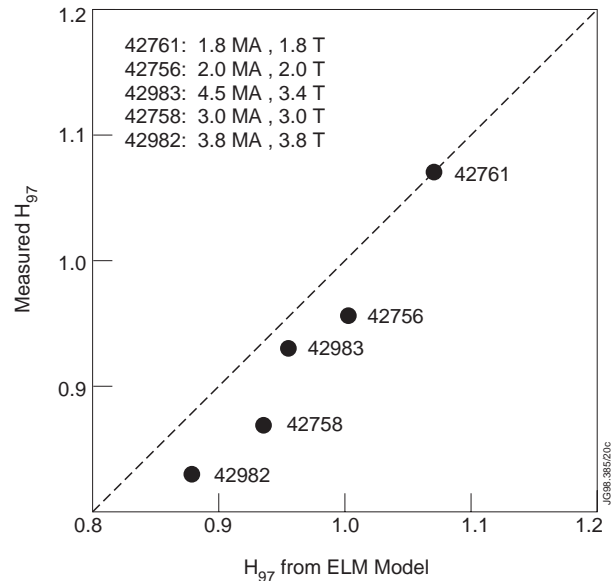

FIG. 12. The measured thermal confinement enhancement factor, relative to the 1997 ELMy H-mode scaling, versus the prediction of the ELM model described in the text. The points are annotated with their pulse numbers and correspond to DT discharges.

charges with higher ELM frequencies which clamp the edge temperature to lower values could result in poorer core confinement as well. At present, the JET edge database is too sparse to draw firm conclusions on this subject. Work is underway to expand the dataset so as to begin to address this question.

This analysis of the influence of ELMs on the global confinement does not address the factors which determine the ELM frequency. Presumably several factors are involved, including vessel conditioning, input power and its margin over the H-mode threshold, and edge magnetic shear. Experiments with different heating schemes [16], with additional deuterium gas fuelling [9, 18], and with impurity seeding [21] have all also been shown to change the ELM frequency and thus the time-averaged edge confinement. Further work is required to ascertain the physics mechanisms behind these changes and to quantify more precisely their influence on global plasma performance.

4.   OPERATING SPACE LIMITATIONS

Tests of ELMy H-mode operation at high current in JET have highlighted the restrictions in the available operating space. Since these restrictions are likely to apply to a next step device it is useful to understand them and their scalings with machine
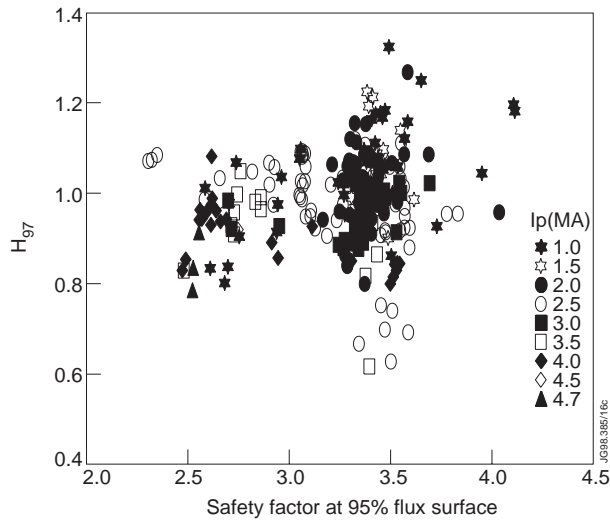
FIG. 13. The confinement of the pulses in the JET steady state ELMy H-mode database, as measured by H_{97}, versus the plasma safety factor, q_{95}.

parameters.

The push to high performance and thus to high current is restricted in JET by the lowest achievable value of q_{95}. Tests of q_{95} values between 2.3 and 4 have shown that the confinement of ELMy H-modes does not depend on q_{95} (Fig. 13). This provides a potential improvement in the performance of a reactor where there are stronger limitations on the toroidal magnetic field than on the plasma current. Indeed, the projections to ITER of our high current pulses are better for lower q_{95} than for $q_{95} \approx 3.3$ as in the ITER reference scenario. One significant difficulty was found which is related to operation at low q_{95}. Strong mode activity with toroidal mode number of 2 was found in several pulses with $q_{95} \leq 2.4$. For this reason, it was felt prudent, given the potentially large disruption forces, to limit high current operation to $q_{95} > 2.4$.

In an ELMy H-mode with predominantly neutral beam heating and thus central particle fuelling, the core density is difficult to vary. In particular, there is a minimum density below which it is impossible to operate even with a well conditioned machine. This density increases with plasma current (Fig. 14) although more slowly than linearly, so that our high current ELMy H-modes tend to operate at a lower fraction of the Greenwald limit than lower current pulses.

During the deuterium preparation for high current DT experiments it became clear that steady operation was difficult due to a spontaneous H-L transition [22, 23]. This back transition was found to
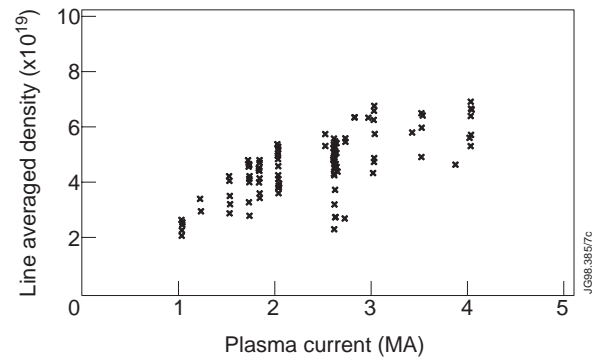

FIG. 14. The central line averaged density of the ELMy H-modes in our steady state database which were fuelled exclusively by neutral beams and had no other form of addtional heating. The discharges are also selected to have a moderate triangularity ($\delta \approx 0.2$) and a good confinement factor ($H_{97} > 0.9$).

occur more frequently at lower input power and at higher toroidal field. Indeed, for a given day, the loss of confinement occurs at an approximately constant value of $(P_{in} - P_{rad})/(n_e B_T)$, as one would expect from an H-mode threshold scaling (Fig. 15). There was some variation from day-to-day, suggesting that vessel conditions were also important. Furthermore, the addition of up to 8 MW of ICRH power in addition to 15-20 MW of NB injection didn't significantly increase the steady state operating space. This last observation is still not understood and is the largest difficulty in attributing the loss of confinement to an H-mode threshold boundary. This attribution is, however, quantitatively as well as qualitatively reasonable. When the back transitions are plotted on a standard L to H threshold diagram, they fall along the same curve (see, for example, Fig. 4 in Ref. [22]). These pulses are near the H-mode threshold, despite their high input power, for two reasons: the steady state density of neutral beam heated ELMy H-modes is high, thus increasing the threshold; and the loss power across the separatrix is significantly reduced by the power required to reheat the plasma between ELMs ($dW/dt \approx 0.4 P_{in}$).

The loss of confinement in our deuterium ELMy H-modes can continue for several energy confinement times and can result in confinement at L-mode levels. Such strong collapses are accompanied by large drops in the density and, in global variables at least, movement away from the H-mode threshold and into a region where one would normally expect the plasma to be in the H-mode regime. There is thus a hysteresis in our data which is of the opposite sign to the hysteresis that has been found in more normal L to H and
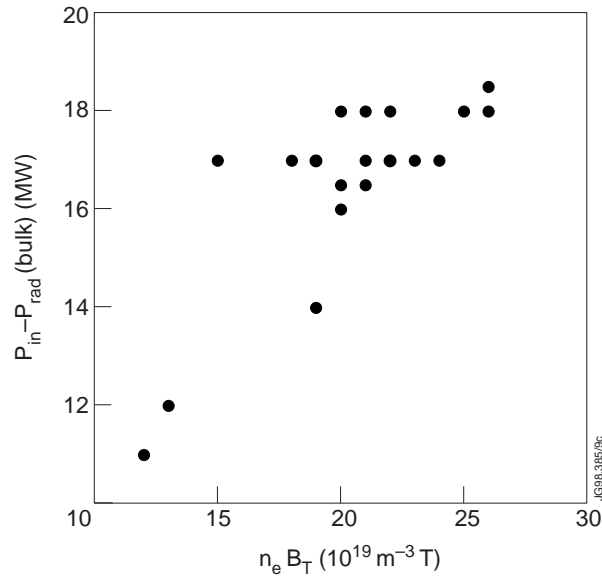
FIG. 15. The net input power to the scrape off layer plotted versus the product of the central line averaged density and the toroidal field, all taken at the time of the loss of confinement in ELMy H-modes. The data are all from one day of operation; there is more scatter when pulses from different days are included, suggesting that vessel conditions also are important in determining when the loss of confinement occurs.

H to L studies where the input power is first stepped up and then gradually reduced [24]. In our case, this hysteresis is due to an edge mhd mode which prevents the formation of the edge transport barrier [22]. When the mode disappears the discharge immediately makes a transition back into an ELM-free H-mode and, after the edge pressure rises to its critical value, an ELMy H-mode. This behaviour is cyclic. Up to three full cycles have been observed in a single discharge. In discharges which exhibit these large losses of confinement, the appearance of the edge mhd mode is, within the time resolution of our diagnostics, coincident with the drop in confinement. Both usually occur following an ELM. It has thus not been possible to establish whether the edge mhd mode causes the loss of confinement or is a consequence of changes in the edge plasma parameters following an H to L transition.

Due to a hardware failure, the final deuterium preparation discharges for the DTE1 were carried out with only half of the divertor cryopump at liquid helium temperature. In order to have exact comparison pulses in DT and T, it was decided to perform most of the DTE1 experiments in the ELMy H-mode regime in the same condition. One would expect the deuterium content of the vessel walls available to be
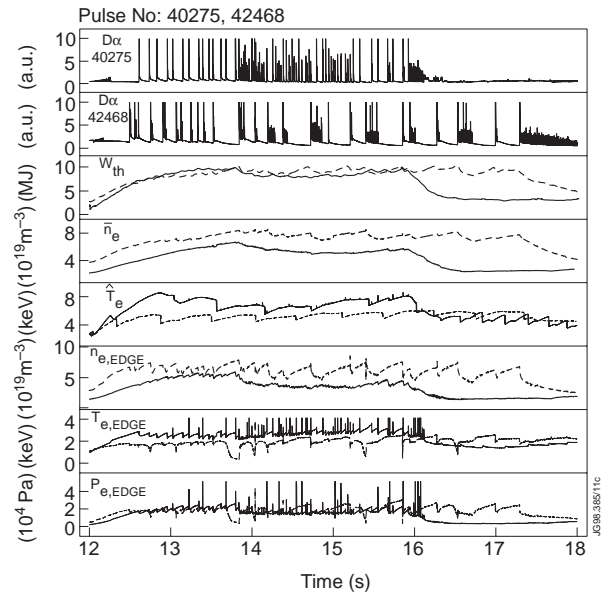

FIG. 16. Comparison of time traces of two 4 MA, 3.4 T pulses, one with only one half of the divertor cryopump cooled to liquid helium temperature (Pulse 40275 - solid curves) and one with the full cryopumping (Pulse 42468 - dashed curves). During several periods with the highest densities in Pulse 42468 the edge plasma becomes opaque to electron cyclotron emission and the edge electron temperature measurement is unreliable (the dips in the dashed curve in the seventh box).

exchanged with the plasma to become higher with only half of the cryopump operational, at least when the pulse repetition rate is comparable. Indeed, comparison of similar pulses with the full divertor cryopump and with half of the cryopump shows marked differences in ELMs and density behaviour.

In Fig. 16, two deuterium discharges at 4MA and 3.4T are compared: discharge 42468 with only half of the divertor cryopump at liquid He temperature and discharge 40275 with the full cryopump operational. The two shots have the same total input power and reached similar confinement enhancement factors ($H_{97} \approx 0.9$). In shot 40275 all the additional heating is provided by NB injection, while shot 42468 is heated by a combination of about 2.5 MW of ICRH (fundamental H minority heating at 52 MHz) and about 16 MW of NB. The plasma magnetic configuration of the two discharges is similar and has relatively low triangularity of 0.2. In both discharges the external fuelling during the additional heating phase is provided only by the neutral beam injection.

In the discharge with only half of the divertor cryopump operational, there is evidence of a higher level of recycling from the vessel walls. In fact, the rate

of increase in the plasma particle content during the ELM free period before the first ELM is higher with half of the cryopump, despite the similar fuelling provided by NBI. Moreover, the fuelling efficiency in the Ohmic X-point phase is lower in the shot with the full cryopump. Finally, both the central and edge steady state densities are 40% higher in the shot with only half of the cryopump operational while the central and edge electron temperatures are lower by about the same fraction.

Perhaps the most noticeable difference between the two discharges is the ELM behaviour. In the discharge with half of the cryopump operational, the ELMs are followed by a period of enhanced D_α level composed of very frequent ELMs and associated with a large drop in stored energy. These compound ELMs are followed by an ELM free period which is longer than the average ELM free period of the shot with the full cryopump.

The ELM behaviour of these two discharges seems to be in contrast with the observation that, in NB heated discharges at constant input power, the ELM frequency increases when the level of external gas fuelling and the density are increased. Moreover, the spontaneous H-L transition was not observed with half of the cryopump, when the toroidal field was increased to 3.8T at 3.8MA. At the same input power and plasma current, the achievement of a steady state with the full cryopump was already marginal at 3.4T. It is possible that the increased recycling and the higher edge collisionality help to stabilise the edge mhd mode observed in discharges with a spontaneous confinement loss. Unfortunately, there are not many discharges which are directly comparable and in particular none with an spontaneous H-L transition, due to the limited period of deuterium operation at high current (1 day) and to the fact that 3.8T was used extensively for the first time during the tritium preparation with half of the cryopump.

The two high performance deuterium-tritium pulses at 3.8MA and 3.8T, 42762 (half cryopump) and 42982 (full cryopump), do not show the same marked differences. We believe that since the second half of the divertor cryopump was switched on just before pulse 42982, it could have had little effect on the overall wall depletion.

All of the operating space limitations described above can be combined into an operating space diagram. Such a diagram is shown for JET in Fig. 17. This diagram is based primarily on deuterium data from low triangularity discharges with the full divertor cryopump operational. Some small changes would
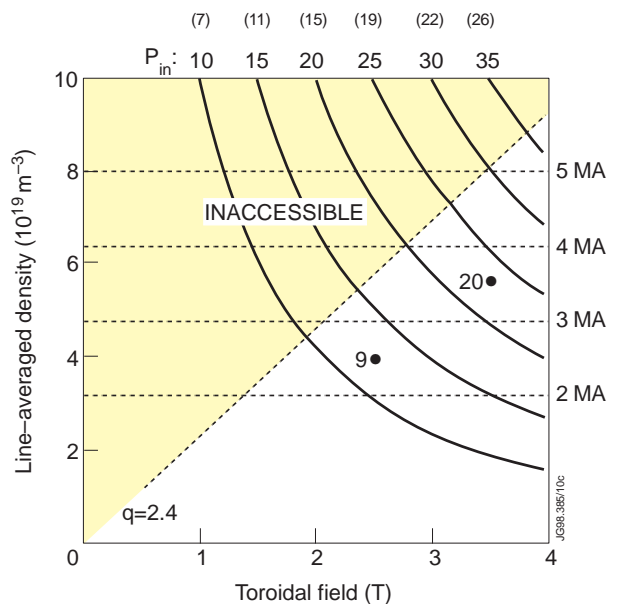

FIG. 17. The operating space diagram for steady state ELMy H-modes in JET. Operation at high current is limited to discharges above $q_{95} = 2.4$, the lower right half of the diagram. The core plasma density is assumed to be one half of the Greenwald limit in steady state. This places a limit on the power necessary to maintain the discharge in H-mode: $P_{LH} = 4.5 B_T n_e^{0.75} R^2$ [26].

be expected, especially in the relationship between current and density, for other conditions. In this diagram we have assumed that our steady state operating point is at 50% of the Greenwald limit, i.e. $n_e = (I_p/\pi a^2)/2$. Furthermore, we use the fact that typically 20% of the input power is lost to radiation and 40% is used to maintain the rate of rise of the core stored energy between ELMs. This means that only 40% of the input power is available to maintain the edge conditions necessary for an H-mode. The two points on Fig. 17 give the positions of the observed loss of confinement in deuterium plasmas at 2.5 MA and 2.5 T and at 3.5 MA and 3.4 T. It can be seen that they fall close to appropriate loss of confinement curves in the diagram. The values in parentheses at the top of the operating space diagram give the necessary input power in 50:50 DT plasmas, assuming that the H-mode threshold is inversely proportional to the isotope mass [25]. This, combined with the increased neutral beam heating power available when injecting tritium from one of the two injector boxes, predicts a significantly widened operating space in DT. Indeed, no difficulty with loss of confinement was observed in the three high current ELMy H-modes which were produced in DTE1.

5. SUMMARY AND CONCLUSIONS

Because of its combination of high performance, quasi-steady nature and robust character, the ELMy H-mode is the preferred operating regime for the next step magnetic fusion device. During DTE1, the fusion performance of ELMy H-modes has been tested at the limits of JET's capabilities. The resulting plasmas performed up to expectations based on DD preparation pulses and thus establish a firm basis for extrapolating to a next step machine. In particular, the JET results, when extrapolated to ITER, predict ignition.

The high current discharges in JET were limited to less than five seconds duration due to technical restrictions on the high power heating systems and to the neutron budget (vessel activation). For this duration these discharges are steady state in terms of energy confinement time but not in terms of current diffusion times and wall equilibration times. Tests at lower currents and with pulse lengths up to 20 s in deuterium plasmas have shown no change in confinement. There is good reason to suppose, therefore, that the high current DT pulses could be extended to truly steady operation with no loss of confinement or performance.

The confinement of our ELMy H-mode discharges above 3 MA is somewhat degraded compared to the most recent global scaling laws. This relative loss of confinement appears to be shared between the edge confinement barrier and the plasma core. A fit to our dataset produces a weaker plasma current scaling than that found in the 1997 scaling law. There are strong collinearities in our dataset, however, and it is not possible to separate the dependencies on current and toroidal field. The separation of plasma current and density is also difficult, although fits to subsets of the data at constant plasma current reproduce the density dependence found when fitting the entire dataset. Other experiments [9, 21] have shown that this density dependence is violated when strong gas puffing and / or impurity seeding is used.

Studies of core mhd activity show no clear differences between pulses with moderate and high plasma current. The ELM behaviour, on the other hand, can be shown to be responsible for at least some of the observed degradation. In this sense, we believe that current global scaling laws for ELMy H-modes are only accounting for some of the changes in confinement due to ELMs. The relatively poor core confinement of some of our high current discharges may also be related to the degradation at the edge, but the present JET edge database is too sparse to allow firm conclusions to be drawn.

This approach of correlating the confinement of our ELMy H-mode discharges to the timing of the ELMs, while useful in focusing attention on the plasma edge, has the disadvantage of not having a predictive capability. Some additional engineering parameter or parameters, which control the ELM behaviour, are required in order to construct a predictive scaling which fits the entire JET dataset of ELMy H-modes. Furthermore, the DTE experiments have clearly shown that there is a significant difference in the mass dependence of the core and edge confinement [7]. Work is underway to develop separate scaling laws for the edge and core confinement. This will strongly challenge the capabilities of current edge diagnostics. More and better data is required if precise results are to be achieved.

Deuterium preparation for operation in DT has highlighted the limited operating space available at high current. An operating space diagram has been generated which is based on the assumption that the loss of confinement seen at high current is due to proximity to the H-mode threshold. Since this threshold is found to scale inversely with the isotope mass, the operating space was predicted to be wider in our tritium experiments. Indeed, our three high current DT pulses did not suffer from a loss of confinement during the high power phase.

In the last day of high current deuterium preparation before DTE1, no loss of confinement was observed, even at power levels where it might have been expected. This is thought to be due to the fact that we were operating with only one half of the divertor cryopump which led to increased recycling levels and higher density, lower temperature edge plasmas. It appears that the mhd instability at the plasma edge, which is the reason for the large hysteresis observed during the loss of confinement, is suppressed in these conditions. Experiments are planned in the new JET operational campaign to test this hypothesis in more controlled conditions.

Acknowledgements

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