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J.G. Cordey, D.C. McDonald and W. Schippers
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
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ABSTRACT

A similarity technique is described in which the temperature and density profiles and fusion performance of ITER and DEMO are determined from the D-T discharges completed on JET. The limitations and errors associated with this technique are also briefly described.

1. INTRODUCTION

Several different techniques are being used to estimate the performance of the next generation of fusion experiments. The most common is to use a scaling expression for the confinement time [1], deduced from the experimental results from a large number of Tokamak experiments. This particular technique has been extensively developed and has been used in the design of the next step tokamak ITER [2]. There are shortcomings of the technique which are discussed in the literature [3], one obvious one is that this particular technique does not give the plasma profiles of density or temperature. Another technique which is also being extensively studied is the development [4] and testing of 1-D theoretical models. Although these models are now highly sophisticated it is not yet clear whether any of them are yet accurate enough to be used for predicting the fusion performances of future devices such as ITER and DEMO [5].

In this note we study a similarity technique, where we use the apparent gyro-Bohm structure of the transport equations to extrapolate from the JET D-T experiments, to similar experiments in ITER and DEMO. Experimental studies, of plasma scenarios similar to those proposed for ITER and DEMO and with ρ^* values closest to those of ITER and DEMO, indicate that plasma transport and global confinement are largely consistent with gyro-Bohm scaling [5,6,7,8]. Possible exceptions are plasmas with high β_N (>2.5) with current profiles that are broad, in comparison with the baseline H-mode scenario, which are commonly classified as hybrid plasmas (9,10). Such plasmas show some evidence for a scaling closer to Bohm [11,12]. Theoretical studies, based on drift wave turbulence, also predict a gyro-Bohm scaling for plasma transport [13,14]. As a result, the majority of predictive simulations for future fusion devices are with transport models which have gyro-Bohm scaling [15,16,17]. Hence, although we will concentrate on obtaining D-T projections for gyro-Bohm scaling, we will also present results for the extreme case of Bohm transport throughout the plasma.

The structure of the remainder of the note is as follows: in Section II, the theoretical basis of the technique is established and then in Section III, a few examples using the JET D-T data and a recent hybrid pulse are given. Finally in Section IV we summarise the results.

2. DERIVATION OF THE SIMILARITY TECHNIQUE

It will be assumed that the plasma is in thermal equilibrium. The heat transport equations for ions and electrons may then be written in the form:

$$\frac{3}{2} n \frac{\partial T}{\partial t} + \nabla . q = P \qquad (1)$$

$$\text{with } q = -n\chi\nabla T,$$

where, n is the density, T is the temperature, P the input power and χ the heat diffusivity.

Assuming gyro-Bohm transport χ can be written in the form,

$$\chi = a^2\, \omega_c\, \rho^{*3}\, F\,(\beta, \nu^*, a/L_T, a/L_n, a/L_M, ...) \tag{2}$$

Here, a is the minor radius, ωc the ion cyclotron frequency, β the plasma beta, ν* the collisionality ($\propto na/T^2$), ρ* the dimensionless Larmor radius ($\propto T^{1/2}/Ba$), L_T the temperature scale length $(\nabla T/T)^{-1}$, Ln the density scale length $(\nabla n/n)^{-1}$, Lm the Mach number scale length $(\nabla M/M)^{-1}$, a the plasma minor radius, B the magnetic field and M the Mach number. There are several other dimensionless parameters that could be included in the function F, such as the safety factor profile q, elongation κ, aspect ratio ε, triangularity δ etc, however it will be assumed that these are chosen in ITER and DEMO to be identical to those of JET. In practise, such a match is difficult to achieve. β_N, also used in this paper, is defined as $\beta_N = (100aB/I)\,\beta$ where I is the plasma current in MA and a and B are in units of metres and Tesla respectively.

We normalise all the lengths in Eq. (1) to the minor radius a, and the temperature, density, power with respect to their central values $T = T_o\,\hat{T}$ etc. where T_o is the central temperature.

The heat transport Eq. (1) in steady state can then be written in the form,

$$K\frac{\partial}{\partial x}\left[x\hat{n}\hat{T}^{3/2}\,\frac{\partial \hat{T}}{\partial x}F\left(\beta_o, \nu_o^*, M_o, \hat{M}, \hat{n}, \hat{T}\right)\right] = \hat{P} \tag{3}$$

where $K = n_o\, T_o^{5/2} / B_o^{\,2}\, a_3\, P_o$

For fixed values of K, β_o, νo*, Mo and fixed profiles of density, power density and Mach number, the temperature profile $\hat{T}$ is unique. That is in two different devices with these constraints the temperature profiles would be identical. Hence we can take D-T pulses from JET and use these to predict the D-T performance of ITER. Now of course this relies on obtaining the same profile of the power density and the same balance of power between ions and electrons in the two devices. This could in principle be obtained with a neutral beam injection system using multiple energies. Similarly by adjusting the particle and momentum input, one could in principle arrange for the density and Mach profiles also to be identical.

The condition K, ν_o^*, β_o constant can be reduced to the more familiar condition

$$T_o \propto a^{1/3}\, B_o^{\,2/3},\; n_o \propto a^{-1/3}\, B_o^{\,4/3} \text{ and } P \propto a^{1/2}\, B_o. \tag{4}$$

where P here is the total input power.

In the next section, the technique will be illustrated with a few D-T ELMy H-mode examples from JET and also a recent hybrid pulse from JET.

3. EXAMPLES

We start with a 3MA D-T ELMy H-mode from JET [18], Pulse No: 42758. The time behaviour of the main parameters is shown in Fig.1.

To extrapolate to ITER ($a = 2m$, $B = 5.3T$) we use Eq.(4) to determine the deuterium and tritium density and ion and electron temperature profiles and then calculate the thermonuclear yield, which is 150MW for this pulse. The power input to achieve this yield is 48MW. Hence the thermonuclear Q for the pulse is 8.1 when one includes the 30MW of α heating in the power input. This particular pulse has only a modest value of β_N (= 1.7).

In table I, a representative set of JET D-T ELMY H-modes is given, along with their extrapolation to ITER. From the table it can be seen that the higher β ITER pulses actually just ignite. A recent hybrid pulse in deuterium is also included at the bottom of the table and one can see this also ignites.

We include similar extrapolations for DEMO, based on a series of proposed power plant designs (5), in Table I. The particular DEMO design is case A, which has parameters $B = 7.0T$, $a = 3.18m$. From the Table, one can see that all of the extrapolations ignite, however only the higher β pulses give the required fusion power output of 4000MW.

There are of course several sources of errors associated with these extrapolations. The error involved in the actual extrapolations are small, since the basic extrapolation is in toroidal field and minor radius a. There is however the question as to whether one can keep the collisonality the same in ITER and DEMO as that of the JET pulses. For example for pulse 42756 the density would have to be larger than the Greenwald limit ($n_{Gr} = G_0 I/\pi a^2$; $G_o = 10^{14} M^{-1} A^{-1}$) the empirically derived maximum density. If one relaxes the collisionality constraint by reducing the density by 33% and keeping the same β the fusion performance is very similar as can be seen in case 42756(b). The scaling of energy confinement time, τ_E, with normalised collisionality ν^* is found to be very weak in both JET [19] and DIII-D [20] and almost non-existent ($B\tau_E \propto \nu^{*-0.01}$) in the global scaling IPB98(y,2) which is based on a multi-machine fit (3). In fact the energy confinement time, τ_E, in the JET and DIII-D studies actually improves with reduced collisionality ($B\tau_E \propto \nu^{*-0.3}$). Hence if anything case (b) will be an underestimate of the performance.

Another potential source of error is not being able to match the particle and momentum source rates in ITER and DEMO to those in JET. From the particle and momentum balance equations one can repeat the analysis in Section II, and derive the necessary particle and momentum source rates so that the density and Mach number profiles match. The particle and momentum input rates from the beams are found to scale as $S \propto B^{1/3} a^{1/6}$ and $E \propto B^{2/3} a^{1/3}$ respectively. In principle as mentioned previously these sources could be matched in ITER by the use of a neutral beam injection system with multi energy beams at differing angles. This of course would also only be possible in the approach to ignition when the NBI is the dominant momentum and particle source. Once ignition is achieved, then if the NBI was switched, off, the momentum and particle sources would change substantially. A similar argument holds for the balance of input power to the ions and electrons. These powers should be in the same ratio as the target plasma on ITER or DEMO and the resulting ion and electron temperatures should also be in the same ratios. A more fruitful approach than modifying the target ITER or DEMO plasma would be to change the sources of particles, energy and toroidal momentum in future JET D-T experiments so that they matched those expected in ITER by the use of pellet injection and ICRH in addition to the NBI heating.

It is also interesting to repeat the extrapolation for the extreme case of Bohm transport throughout the radial profile. For this particular case the power input in equation (4) is replaced by $P \propto a^{4/3} B^{5/3}$. The results are shown in Table II for the two high β Pulse No's: 42756 and 77993. It can be seen from the table that modest values of Q (≈2-3) are obtained for ITER and ignition is achieved in DEMO. Thus, we see in DEMO at least energy confinement will not be a key issue, and issues such as fuelling and ash removal will be more relevant. The Q values in ITER could be increased further by increasing the β or the currents in the two pulses. In this way, values close to the target Q of 10 could be achieved.

SUMMARY

A similarity technique has been described such that JET D-T discharges can be used to determine the performance of the next generation of fusion experiments such as ITER and DEMO. One key feature of this technique is that the radial temperature and density profiles are obtained, enabling an accurate estimate to be made of the D-T fusion yield. It is found that with gyro-Bohm transport throughout the radial profile, provided that the β is large enough ($\beta_N > 2.6$) then ITER will ignite, and even in the extreme case of Bohm transport throughout DEMO will ignite. Differences in particle sources and input torque between JET and the other machines may affect these results. Further JET D-T studies with better matches in these parameters would greatly increase the confidence in such extrapolations.

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Table I

JET				ITER B = 5.3T					DEMO B = 7.0T				
Pulse No.	**I(MA)**	**B(T)**	β_N	**I (MA)**	**Pin (MW)**	P_{fusion} **(MW)**	**Q**	n/n_G	**I (MA)**	**Pin (MW)**	P_{fusion} **(MW)**	**Q**	n/n_{Gr}
42762	3.8	4	1.3	11	46	62	1.9	0.7	23	76	926	∞	1.45
42758	3	3	1.7	12	48	150	8.1	1.1	25	81	2260	∞	1.67
42756a	2	2	2.6	12	67	356	∞	1.4	25	112	4676	∞	2.1
42756b	2	2	2.6	12	67	382	∞	0.93	25	112	4287	∞	1.3
Hybrid 77933	2	2.3	2.1	10	71	462	∞	1.2	22	118	5527	∞	2.1

Table 1: The predicted performance in ITER and DEMO from steady state ELMy H-mode pulses in JET with a 50:50 D-T mixture, and a deuterium only recent Hybrid pulse (Pulse No: 77933).

Table II

JET Pulse No.	ITER B = 5.3T				DEMO B = 7.0T			
	I (MA)	**Pin (MW)**	P_{fusion} **(MW)**	**Q**	**I (MA)**	**Pin (MW)**	P_{fusion} **(MW)**	**Q**
42756b	12	247	382	2.2	25	730	4287	∞
Hybrid 77933	10	241	462	3.1	22	712	5527	∞

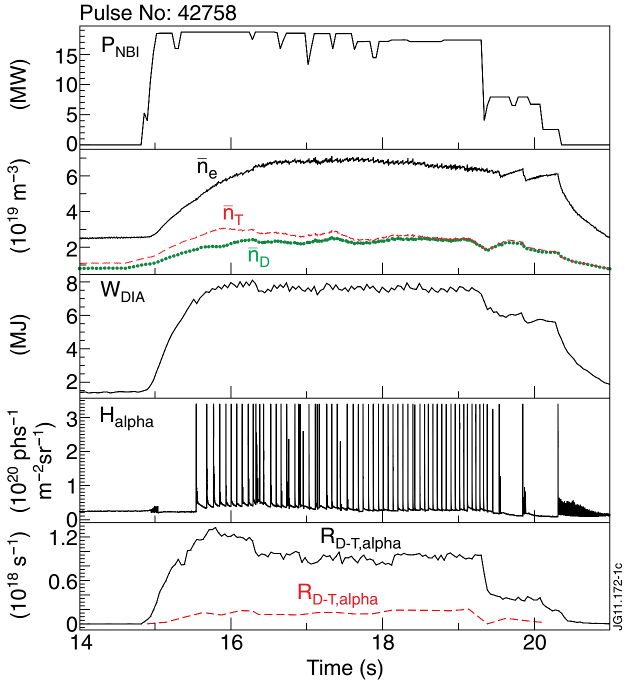

Figure 1: Time trace of key parameters for the JET D-T Pulse No: 42758. Parameters shown are: (a) the injected NBI power; (b) the line average electron (black solid), deuterium (green dotted) and tritium (red dashed) densities; (c) the diamagnetic stored energy; d) the H_{α} divertor light; and (e) the total (red solid) and thermal-thermal (blue dotted) D-T neutron fluxes.