JET–P(99)56

J G Cordey et al

A Demonstration of the ‘Isotope Wind Tunnel Principle’ in JET and its use in Predicting Reactor Performance

JET–P(99)56

A Demonstration of the ‘Isotope Wind Tunnel Principle’ in JET and its use in Predicting Reactor Performance

J G Cordey, B Alper, R Budny1, J P Christiansen, I Coffey,
K Erents, P Harbour, L D Horton, K Lawson, G F Matthews,
G Saibene, R Sartori, J Strachan, K Thomsen.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,
[1]PPPL Princeton University, Princeton, NJ, USA.

Preprint of a Paper to be submitted for publication in Phys. Rev. Letters

January 2000

ABSTRACT

ELMy H-mode pulses have been obtained with different hydrogenic isotopes (H and D) but having the same profiles of the dimensionless parameters ρ^*, β, ν^* and q, to test whether the confinement scale invariance principle is valid in a tokamak. The fact that the confinement times, the ELM and sawtooth frequencies in the two pulses all scale as expected suggests that the invariance principle is satisfied through the plasma radial extent, in spite of the differing physical processes taking place in the plasma centre, core and edge regions. An application of this “isotope windtunnel technique” to predicting D-T performance of next step devices is discussed.

In tokamak discharges, such as the steady state ELMy H-mode, the physical processes change dramatically as one moves out in minor radius. In the central region the temperature gradient is controlled by MHD modes (sawteeth), whilst outside in what is known as the core confinement region the transport is thought to be due to small scale Larmor radius (r_i) size turbulence, such as that caused by the ion temperature gradient instability. Finally in the edge region the transport is almost neoclassical with intermittent MHD events (ELMs) controlling the steepness of the gradients in this region.

From theoretical analysis, in particular the confinement scale invariance principle(1), (2), it should be possible to describe the transport properties in all three regions in terms of the profiles of the basic dimensionless plasma physics parameters $\rho^*(\propto(MT)^{1/2}/aB)$, $\beta(\propto nT/B^2)$, ν^* ($\propto na/T^2$) and q ($\propto B\kappa/Rj$). The thermal diffusivity should have the form

$$\chi \propto \frac{Ba^2}{M} F(\rho^*, \beta, \nu^*, q, ...) \tag{1}$$

where the form of the function F will be different in each of the three regions.

One method of checking whether the invariance principle is correct is to complete wind tunnel or identity experiments on different tokamaks. This involves setting up discharges on different tokamaks with the same profiles of ρ^*, β, ν^* and q and then inspecting whether the thermal diffusivity scales as Ba^2/M. These type of experiments have been completed on DIII-D and JET (3) and the thermal diffusivities in the core confinement region do indeed scale as expected.

An alternative technique to intermachine experiments is to compare plasmas with different isotopes in the same machine. The isotope mass M enters only through the ion Larmor radius in the parameter ρ^*. Thus by changing the toroidal field one can in principle if the invariance principle is correct obtain discharges with different isotopes and the same profiles of ρ^*, β, ν^* and q. The confinement time and ELM and sawtooth frequencies should then scale as $\tau_e \propto M/B$, $f_{ELM} \propto B/M$ and $f_{saw} \propto B/M$ respectively if the invariance principle is correct in the three regions.

To keep the profiles of the four basic parameters ρ^* ($\sim M^{1/2}\,T^{1/2}/aB$), β($\sim nT/B^2$), ν^*($\sim na/T^2$) and q ($\sim B\kappa/Rj$) fixed means that the following scalings for the dimensional parameters must hold

$$B \propto M^{3/4}\,a^{-5/4} \tag{2a}$$

$$j \propto M^{3/4}\,a^{-17/4} \tag{2b}$$

$$n \propto M\,a^{-2} \tag{2c}$$

$$T \propto M^{1/2}\,a^{-1/2} \tag{2d}$$

To match the profiles of B and j in a deuterium plasma to those of a hydrogen plasma, such that they scale in the manner given by equation (2a) and 2b) is quite straight forward. The field B and current in the deuterium plasma have to be $(2)^{3/4} = 1.68$ times those of the hydrogen plasma. In the experiments described below we chose the field and the current in the hydrogen plasma to be 1T and 1MA respectively and hence these same quantities in the deuterium plasma are chosen to be 1.68T and 1.68MA.

Matching the density and temperature profiles of the hydrogen and deuterium discharges is less straightforward, although is in principle possible since we can control the temperature profile using the two different energy neutral beam boxes and the density profile can be controlled to some extent by the edge gas source. One major difficulty though is the lack of a really accurate measurements of the edge profile. The Lidar diagnostic gives accurate measurements to within about 10cm from the separatrix and there is also a vertical line integral density measurement located at R = 3.75m from a far infrared Interferometer system. Thus in the edge region we essentially only have pedestal values for both the density and temperature. Matching these edge pedestals does seem to be sufficient though to give a good ELM frequency match as will be seen later.

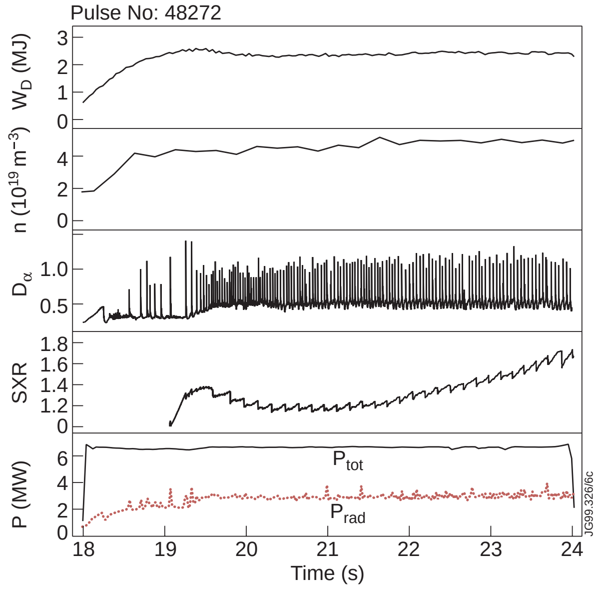

Fig.1: Diamagnetic stored energy, density, D_α, central soft X-ray channel and total input power versus time for deuterium pulse 48272.

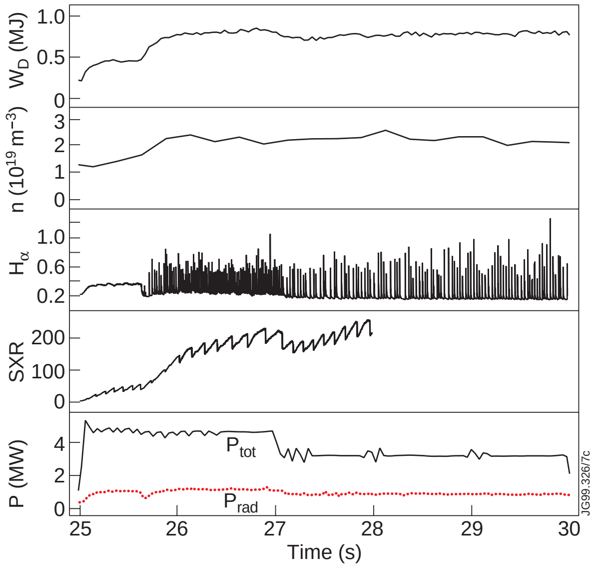

Fig.2: Diamagnetic stored energy, density, H_α, a central soft X-ray channel and total input power versus time for hydrogen pulse 48338.

Turning to the experimental procedure we first completed a gas fuelling scan at fixed power with deuterium injection into deuterium. The time traces for a typical pulse with moderate gas input are shown in Fig. 1. Then switching to hydrogen NBI into a hydrogen plasma we adjusted the power level until the scaled temperature profile matched that of the deuterium pulse of Fig. 1. The time dependent traces for this particular pulse 48338 are shown in Fig. 2. The dependence of the scaled ELM frequency, sawtooth frequency and thermal confinement time versus the scaled power is shown for the complete hydrogen and deuterium datasets in Figs. 3a-c. From these figures it can be clearly seen that all the frequencies and confinement times are very well matched for the deuterium pulse 48272 and the hydrogen pulse 48338. The full parameter sets for these pulses are given in Table I.

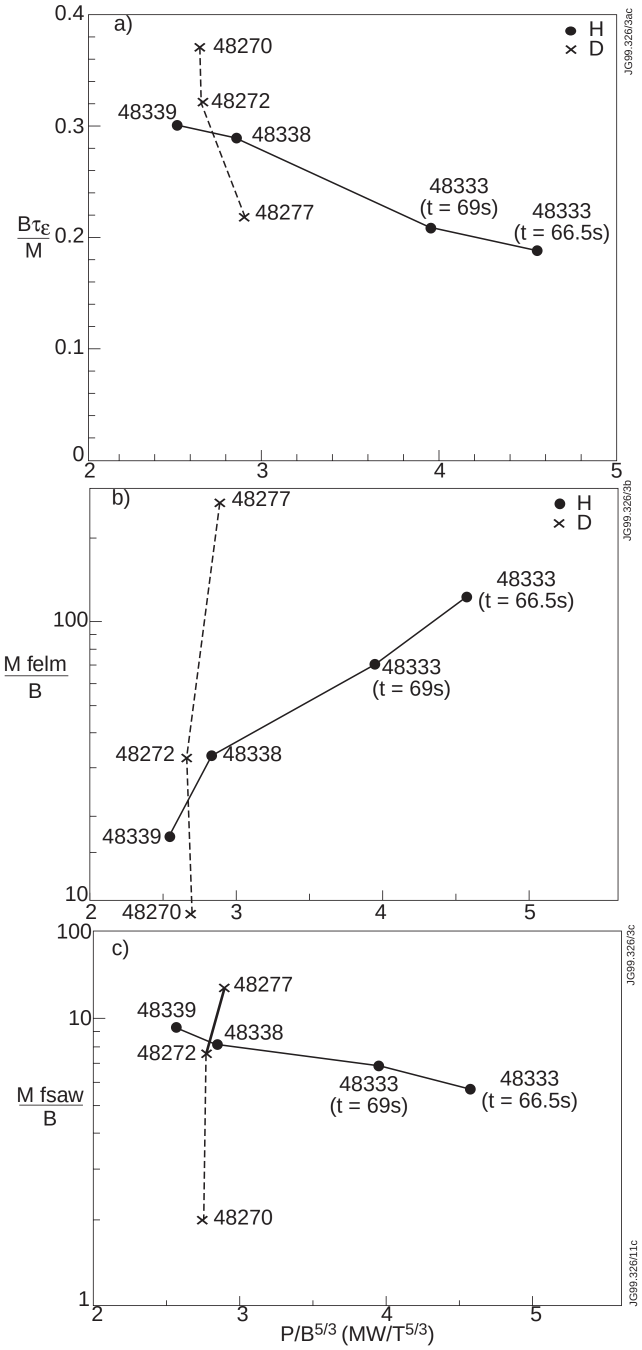

Fig.3: a) Dimensionless confinement time $\frac{B\tau_\varepsilon}{M}$ *versus the scaled power* $P/B^{5/3}$. *b) Dimensionless ELM frequency versus the scaled power* $P/B^{5/3}$. *c) Dimensionless sawtooth frequency versus the scaled power* $P/B^{5/3}$.

Turning to the local transport analsis, using the TRANSP(4) code. The only temperature profile measurement that was available in these pulses as Te the Lidar diagnostic. The Lidar density profile was also available and is used in the analysis. Unfortunately no ion temperature measurements were available in these plasmas due to the unavailability of one of the neutral beam injector boxes. Inspection of similar pulses in which ion temperatures measurements were available reveals that the ion temperature is very close to the electron temperature, so the assumption $T_i = T_e$ was made throughout. For both the deuterium (#48272) and the hydrogen pulse (#48338) the measured neutron yield and diamagnetic measurement of the stored energy were accurately reproduced by the TRANSP code, from which it can be concluded that the input data is self consistent.

Table I:

Pulse No:	**48338**	**48272**
Isotope	H	D
Time (s)	29	21
B (T)	1	1.7
I (MA)	1	1.7
Power (MW)	2.83	6.45
W_{th} (MJ)	0.82	2.42
τ_{th} (s)	0.29	0.37
$\frac{B\tau_{th}\,(s)}{M}$ (TS)	0.29	0.32
$\frac{Mf_{ELM}\,(s)}{B}(H_Z/T)$	33	33
$\frac{Mf_{saw}\,(s)}{B}(H_Z/T)$	8.0	7.5

JG99.366/1c

The profiles of the dimensionless parameters ρ*, β and ν* for the two pulses are shown in fig.4a-c. The matches of the hydrogen and deuterium profiles are very good for all of the dimensionless variables right out to the edge region. The profiles of the non-dimensional effective χ are shown in Fig.5. These profiles are very similar right out to the edge region'r'/a = 0.9, the difference in the central region being within experimental errors.

Having established that the invariance principle is satisfied right across the radial profile we now investigate how the "isotope wind tunnel" technique could be used to predict the performance of future devices. From eq. (2a) which can be rewritten in the form

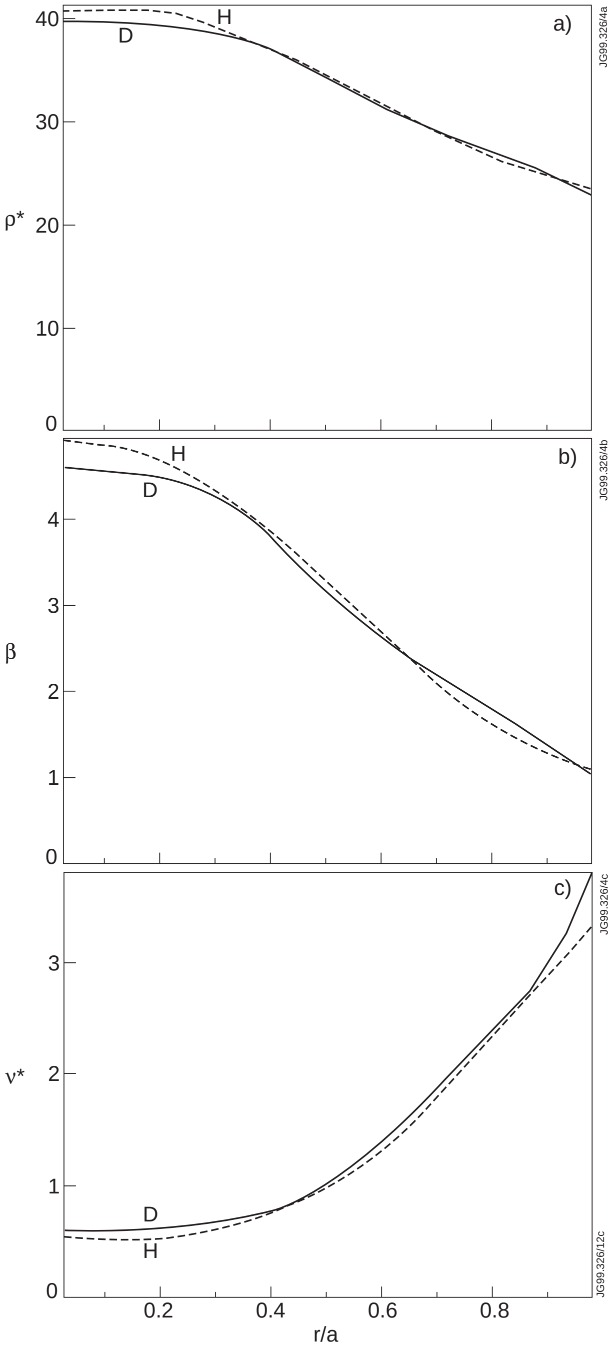

Fig.4: a) The normalised Larmor radius $\rho^*(\equiv \rho i/a)$ (arbitrary units) versus the radial variable 'r/a'. b) The plasma β (arbitrary units) versus the radial variable 'r/a'. c) The plasma collisionality ν^* ($\propto na/T^2$) versus the radial variable 'r/a'.

$$a^5 \propto M^3/B^4, \qquad (3)$$

we see that one can use a hydrogen plasma in a smaller device to predict the D-T, performance of a larger device. Possible examples are to use hydrogen plasmas in JET to predict the performance of a D-T plasmas in RC-ITER and then to use hydrogen plasmas in RC-ITER to predict the D-T performance of a reactor scale device. The main parameters of these examples are given in Table II.

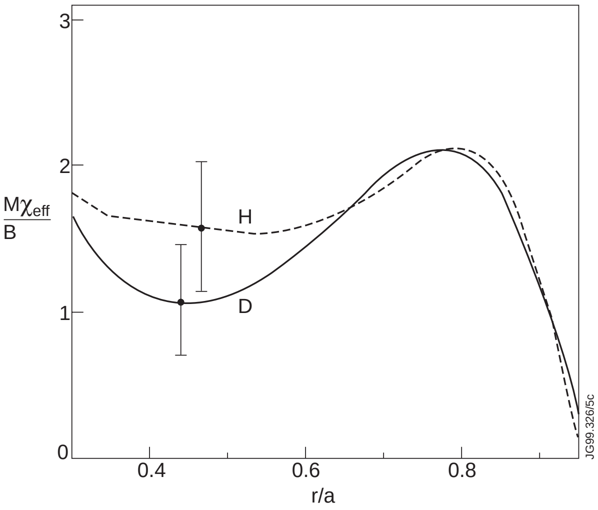

Fig.5: Dimensionless effective thermal diffusivity M χ_{eff}/ B(m^2/S/T) versus the radial variable ‘r/a’.

For the JET machine it is assumed that the full size device capability is recovered, that is the minor radius is increased from a = 0.9 to a = 1.2, and also that there is a major upgrade in the injected power to the order of 50MW so that a reactor relevant β_n(~ 2.5) is obtained at full field (B = 4T). The RC-ITER parameters are assumed to be those of one of the options being studied in Europe, the remainder of the parameters are R=5.5m, I=13MA, κ_x=1.9, other options will give a similar result. The parameters of the reactor are taken to be similar to those of the ITER FDR.

Table II:

Machine	**JET (Full size)**	**RC-ITER (identity)**	**RC-ITER**	**Reactor (identity)**
Isotope	H	D—T	H	D—T
a	1.2	1.7	1.7	2.8
B	4	5.16	5.16	5.7

JG99.366/2c

REFERENCES

1) B.B. Kadomstev, tokamaks and dimensional analysis, Sov. J. Plasma Phys. 1 (1975) 295-297.

2) J.W. Connor, J.B. Taylor, Scaling laws for plasma confinement, Nucl. Fusion 17 (1977) 1047-1055.

3) T.C. Luce,et al., “Implications from Dimensionless Parameter Scaling Experiments” Proc. 16th Int. Conf. On Plasma Physics and Controlled Nuclear Fusion Research, Oct 7-11, 1996, Montreal, Canada, Vol. 1 p611 (IAEA, Vienna, 1997).

4) R.V. Budny, et al., Nucl. Fusion **32** (1992) 429.

5) R.Aymar, V.Chuyanov, M.Huget, R.Parker and Y.Shimomura. “ITER Project: A Physics and Technology Experiment” Proceedings of the 1996 IAEA Meeting Vol. 1 p3 .