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D-T Mixture Control with Neutral Beam Fuelling and Importance of Particle Recycling and Isotope Exchange in the JET ELM-free H-mode

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1. INTRODUCTION

The ELM-free hot-ion H-mode regime had been investigated in the JET Mk II divertor configuration over a wide range of plasma conditions in deuterium (DD) discharges prior to the start of the recent DT campaign (DTE1). Experiments in DD with neutral beam (NB) heating alone (up to 19MW) and also with supplementary RF heating (up to 25MW combined heating power) were performed, at plasma currents up to 4.2MA and toroidal field up to 3.8T. Characteristics of the regime such as: confinement and DD fusion performance [1]; MHD stability (sawteeth, outer modes and ELMs) [2]; and influence of particle recycling [3], were all extensively investigated in DD. The optimum experimental conditions for exploitation in DT of the ELM-free regime could thus be defined [4], except the prescription for obtaining the ideal D:T fuel mix in the plasma. Preparatory DT experiments described in this work were designed to address this question and their interpretation has also yielded new insight into the contribution of recycled particles to fuelling (even in the presence of strong NB injection), and also the relative transport of tritium and deuterium within the plasma (“particle mixing”).

2. DD REFERENCE AND DT EXTRAPOLATION

Some specific time traces for a high-performance DD ELM-free H-mode are shown in Fig. 1. A particular feature, observed under prevailing low recycling conditions, is that the rise of the plasma deuterium content closely matches the beam-fuelled particle input. Low recycling and low edge density are necessary for good confinement, an observation which may be understood in terms of a neoclassical model for ion heat transport through the H-mode transport barrier [5]. The pre-programmed gas waveform was optimised experimentally to control sawteeth and at this magnitude had little effect on the global density rise. The TRANSP code was used to predict the DT fusion power using data from the above DD discharge. The result can be expressed as:

$$P_{DT} = 4f(1-f)\times 6.2MW + 2f\times 0.13\times P_{NB}^{D^0} + 2(1-f)\times 0.20\times P_{NB}^{T^0} \qquad (1)$$

where the terms represent the thermal and beam-plasma (D–T and T–D) contributions, respectively. The parameter f represents the fraction of tritium in the plasma, assumed to be uniform throughout the volume. The higher T–D beam-plasma reactivity (for the same power) suggests it is advantageous to maximise the 160kV T^0 beam contribution (up to 11MW was available). The rest of the 19MW NB power is assumed to be made up with 80kV D^0 beams; equation (1) then has an f dependence which maximises P_{DT} at f=0.46. The ratio of T:D NB fuelling is about 3:4 for the chosen beam-mix. If the plasma fuelling during the ELM-free period is dominated by NB fuelling (which is one possible interpretation of the data in Fig. 1), the plasma mix would then reflect that of the beams i.e. f=0.43, close to the optimum in this parameter. However, from the DD discharges it was not possible to establish the relative contribution to plasma fuelling from the beams and from recycled particles; this can be supposed to be in the ratio 1: f_W. In particular, in a DT discharge, if f_W is significant, and if furthermore it is postulated that the isotopic composition of the recycling flux reflects that of the walls/divertor surfaces, achieving the desired plasma D:T composition would require control of the D:T content of the recycling surfaces. This crucial aspect was confirmed in the series of experiments described in the following section.

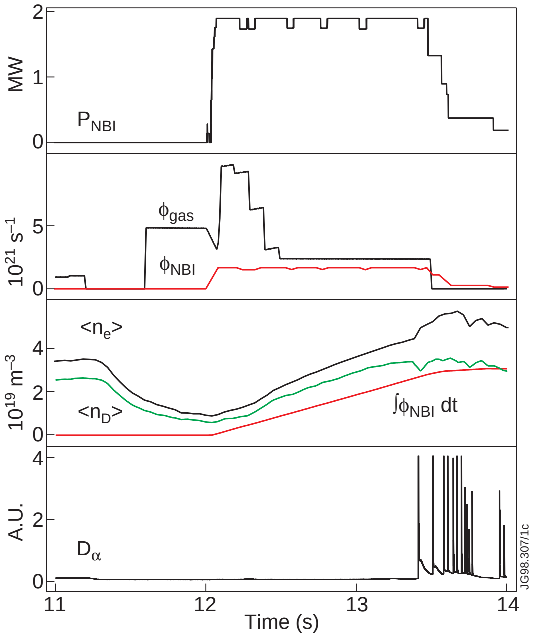

Fig. 1 Time traces for a high performance ELM-free discharge #40305 in deuterium; 3.8MA, 3.4T, 19MW NBI (+ 3MW ICRH, not shown)

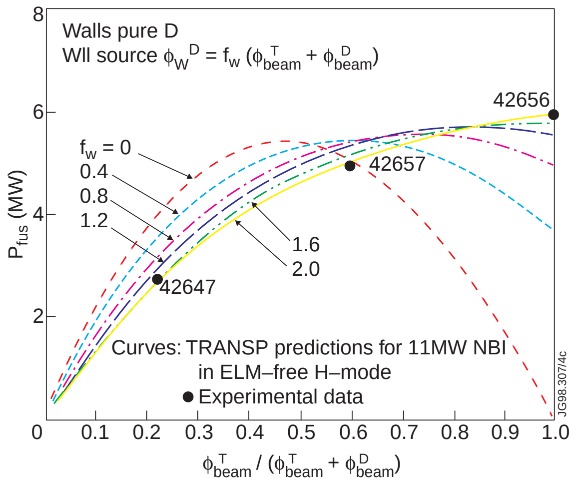

Fig. 2 Predicted and achieved P_{DT} versus beam mix for an ELM-free plasma 11MW NBI, versus beam-mix and f_W

3. DT MIXTURE CONTROL EXPERIMENT

The principle of the *mixture control experiment* was to scan the beam D:T mix from zero to 100% at constant power under conditions where the recycling particles consist of deuterium only. Since only the 160kV neutral injector had been commissioned in tritium, this dictated a power level of 11MW for the experiment. A predictive TRANSP run was therefore carried out for an 11MW NB heated DD reference discharge, resulting in an equation similar in form to (1). Using this, P_{DT} was computed for various beam-mixes between zero and 100% tritium. For each beam-mix, f was first computed for various values of f_W (assuming the composition of recycled particles was pure deuterium). The family of curves for P_{DT} versus beam-mix shown in Fig. 2 is thus obtained; each curve is identified with a value of the parameter f_W. Note that the case with 100% T beams is the most sensitive to f_W, since f_W=0 would imply f=1 and hence zero DT reactivity. This procedure forms the basis of the mixture control experiment, carried out under low recycling conditions when the vessel surfaces had not been exposed to significant tritium (especially from gas fuelling which is effective at loading the walls). Deuterium was used to fuel the target plasma and also for the gas puffing located in the divertor, from where communication with the main chamber is via leakage paths of limited conductance. Previous experiments [3] involving selective hydrogen loading of the main-chamber inner-wall surfaces suggested that the latter was the most important location with respect to influence of recycling on plasma fuelling. In Fig. 2, the best match to the experimental data is obtained for the curve labelled f_W=2. This result lead to the unambiguous conclusion that the vessel walls should be pre-loaded to reflect the desired plasma D:T mix for the high performance DT discharges. The experimental procedure adopted is independent of the particular plasma regime and could be applied equally well to any DT plasma with NBI heating.

4. TRANSP INTERPRETATION OF MIXTURE CONTROL EXPERIMENT

In the TRANSP code the *total* hydrogenic flow is determined from experimental input data and ascribed to a diffusive + non-diffusive ("convective") representation i.e.

$$\Gamma_D + \Gamma_T = -D_D\nabla n_D + n_D v_D - D_T\nabla n_T + n_T v_T \tag{2}$$

In the *proportional diffusivities model*, D_T/D_D = constant (=1 in the present work). This defines the diffusive flow of each species and also the total convective flow. There is one further degree of freedom remaining, namely the ratio of the convective flows of each species. This is defined by applying the constraint v_T/v_D = constant (=1 in the present work). If the value of D is chosen to be small (*i.e.* $D/v << n/\nabla n$) the model reduces to the *constant velocity* case where the T^+, D^+ flows are *coupled*. For $D/v >> n/\nabla n$, the diffusive terms dominate and the flow of each species is driven by its own density gradient; this situation can give rise to *opposing flows*. The range between these two limiting particle flow regimes was investigated by performing TRANSP runs with $D_T(r/a) = D_D(r/a) = D_0$ for $0.01<D_0<10\ m^2s^{-1}$. Large values of D_0 allow each species' flow to respond to its own density gradient, in this case facilitating inflow of recycled D^+ and outflow of beam-fuelled T^+; low values (constant velocity limit) result in higher central tritium concentration and peaking of the n_T profile (Fig. 3). The total P_{DT} is progressively more sensitive to the central n_T as the proportion of T beams is reduced. It is found that D_0=0.2 m^2s^{-1} fits all three discharges in the scan well, e.g. Fig. 4. For this value of D_0 it is found that the gradient-driven terms in equation (2) are most significant, except near the plasma edge where the source due to recycled neutrals (as modelled by TRANSP) is large. Varying the recycling source in TRANSP (by a factor of 5) has little effect on the evolution of the central tritium concentration, but causes a corresponding variation in the magnitude of the term $n_D v_D$ near the edge (through v_D). Since v_D/v_T =1, this also changes $n_T v_T$; however, this term is small since n_T/n_D tends to zero at the edge (Fig. 3). Particle confinement times corresponding to the different recycling levels encompass the values computed from the EDG2D/JETTO code for similar ELM-free plasmas [5]. From the TRANSP analysis it may be stated in

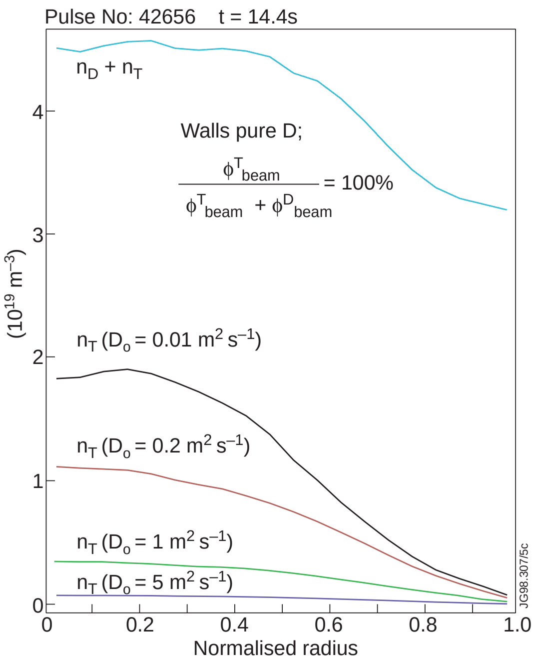

Fig. 3 TRANSP computation of n_T profile at end of ELM-free phase, 100% T NB case, for various values of D_0

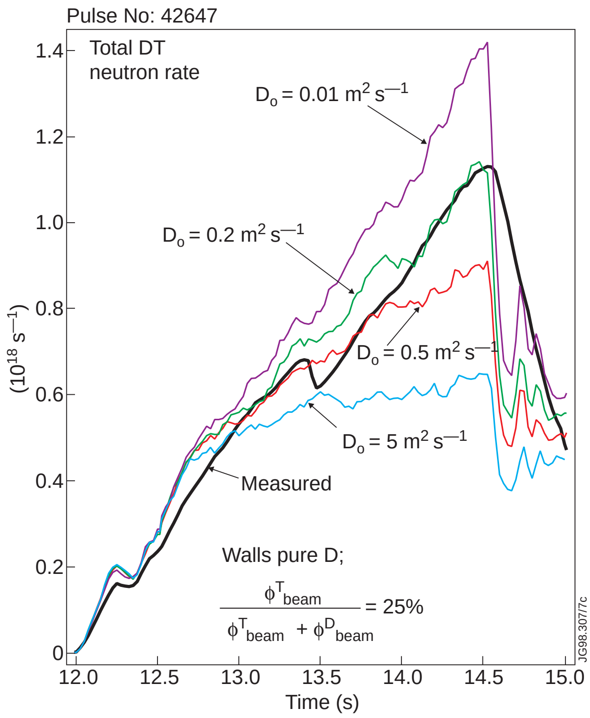

Fig. 4 Comparison of measured P_{DT}, 25% T NB case, with TRANSP calculation for various values of D_0

summary that the series of discharges with different T beam mixes can be described consistently by the same particle mixing model in which the flow of each species is driven mainly by its own density gradient. The assumption of radially constant diffusion coefficient is certainly not unique, in particular, a functional form of D_0 which increases towards the edge could also be adopted instead of invoking an increase in the convective term there; such a representation was used to describe particle mixing in the JET Preliminary Tritium Experiment [6] and can also describe tritium transport in transient gas puff experiments in the ELMy H-mode [7]. The main result here is to demonstrate that the mixture scan data can be explained using a simple particle transport model without invoking additional processes (e.g. involving charge-exchange) as the dominant mechanism influencing the plasma isotopic composition.

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