DT FUSION POWER PRODUCTION IN ELM-FREE H-MODES IN JET

The JET Team[1]
(Presented by F.G. Rimini)

JET Joint Undertaking,
Abingdon, Oxfordshire,
United Kingdom.

Abstract

Experiments in the ELM-free Hot-Ion H-mode regime have been carried out in Deuterium-Tritium plasmas in JET. Initial experiments undertaken at constant NB power, around 11 MW, demonstrated that core fuelling was dominated by wall/target recycling rather than NB fuelling and made it possible to arrange an optimum core DT mix by adjusting the DT mix in wall/target, gas and NB. High power experiments at 4.2MA/3.6T have successfully and reliably delivered fusion power (P_{DT}) up to 16.1 MW and plasma stored energy (W_{DIA}) of 17 MJ. The results are in good agreement with extrapolations, carried out with TRANSP and JETTO codes, from similar deuterium discharges. Transiently, values of Q_{tot} around 0.9 ±0.1 were achieved, consistent with values of $n_{DT}(0)\ \tau_E\ T_i(0) \sim 9 \times 10^{20}\ m^{-3}$ s keV. The ratio of fusion power to input power Q_{IN} is in excess of 0.6. There are indications of an isotope effect on the edge pressure pedestal, however no net dependence of global confinement on isotopic plasma composition has been found.

1. INTRODUCTION

The first pilot experiments using 10% tritium in deuterium in the ELM-free H-mode at JET produced 1.7MW of fusion power as reported at the 1992 IAEA [1].Thereafter the JET programme turned to the study of two divertor designs of increasing closure. The impact of these changes on the ELM-free regime in deuterium were described at the IAEA meetings in Seville 1994 [2] and Montreal 1996 [3]. Since the Montreal meeting, the properties of ELM-free Hot-Ion H-modes with combined Neutral Beam (NB) and Ion Cyclotron Resonance Frequency (ICRF) heating at the Hydrogen minority resonance have been extensively explored. At the same time, the understanding of the MHD stability of the regime progressed with the identification of the so-called Outer Mode as an ideal external kink, driven by the edge current gradient. A method for mitigation and avoidance of the Outer Mode by decreasing the plasma current during the ELM-free phase was successfully developed. As a result the performance, robustness and reliability of the regime have been improved, extending the DD neutron yield to $5.2\times10^{16}\ s^{-1}$ at 3.8 MA/3.4 T with combined NB+ICRH, thereby making the regime an ideal candidate for experiments in DT.

2. DT MIXTURE CONTROL AND PARTICLE TRANSPORT EXPERIMENTS

In ELM-free H-modes in deuterium the plasma density rise is of the same order of the NB fuelling, but it is not possible to establish the relative contribution to the plasma fuelling from the beams and the wall recycling sources.

In the DT mixture control experiments the beam mix was varied from 100 % deuterium to 100 % tritium at constant power, in the range of 11 MW, with deuterium recycling and gas fuelling. The TRANSP code was used to predict, on the basis of a pure deuterium discharge, the DT fusion power as function of the plasma and NB DT mix: For each NB mix, the fusion power P_{DT} was then computed for various values of the contribution f_W of recycling, assumed to be pure deuterium, relative to that of NBI fuelling. The set of curves thus obtained can be compared with the measured P_{DT} (Fig. 1). Note that the 100 % T beams case is the most sensitive to f_W. In Fig. 1 the best match to the experimental data is found for

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[1] See Appendix to IAEA-CN-69/OV1/2, The JET Team (presented by M.L.Watkins)

$f_W = 2$, indicating that wall recycling plays a considerable part in the plasma composition in the ELM-free regime, even in low recycling conditions. The insights from these experiments made it possible to arrange an optimum core DT mix by preparing the recycling surfaces to achieve the desired isotopic mix.

The spatial variation between D and T sources in the DT mixture experiments allows a more detailed analysis of particle transport by the TRANSP code under the assumption of a radially constant diffusion coefficient D_o. Additionally, a common local convection velocity is imposed on both species, sufficient to satisfy the total hydrogenic particle balance. Within the uncertainties of the TRANSP transport model, the study shows that this series of discharges can be described consistently by the same particle mixing model in which the flow of each species is driven mainly by its own gradients; the value of the core particle diffusion coefficient is of the order of the effective heat conductivity χ_{eff} The assumption of D_o = const. is, however, not unique. A functional form of D_o which increases towards the edge could also be adopted, as was done to describe tritium transport in transient gas puff experiments in JET ELMy H-modes [4].

3. OVERVIEW OF HIGH POWER EXPERIMENTS

The DT experiments in the Hot-Ion ELM-free were carried out first in the standard 3.8 MA / 3.4 T scenario, both with NBI alone and with NBI + ICRH. The NB only case reached 12.3 MW of fusion power with 21.6 MW of input power, while the combined heating case delivered 12.9 MW of fusion power for 22.6 MW of total input power, close to that expected on the basis of DD performance if the effect of alpha heating is included. In both cases the Tritium concentration was of the order of 50 % in the core. A second set of experiments was performed at higher plasma current and toroidal field, 4.2 MA / 3.6 T, to exploit the full NB power capability and the expected improvement in confinement and ELM stability with plasma current. A significant gain in performance was thus achieved, resulting in a new record in fusion power, 16.1 MW, and stored energy, 17 MJ, for an input power of 25.7 MW. The thermonuclear fusion power reaches 60 % of the total DT fusion power. No alpha particle driven Toroidal Alfvèn Eigenmodes (TAE) were observed, which is consistent with theoretical analysis [5].

The achieved level of DT performance depends in part on the existence of isotope effects on confinement and MHD stability. In the DT experiments performed to study alpha particle heating [6] an increase of the density, ion and electron temperatures close to the edge transport barrier with increasing isotopic mass was measured [7]. In this set of data, however, the global confinement time does not vary with plasma composition (Fig. 2). In the high power experiments, within 10 % the loss power is found to be the same function of stored energy in DD and DT. On the other hand, local confinement analysis suggests that in the core the effective thermal conductivity follows gyro-Bohm scaling and hence degrades with increasing mass. The fusion power is close to what is predicted by the transport code TRANSP, including alpha particle heating but excluding isotope effects. The experimental maximum net isotope effect maybe of the order of 1 MJ. In summary, isotope effects on local confinement have been identified, both in the core and in the edge transport barrier, but the net effect on global confinement is small within the uncertainties of the analysis.

4. DT FUSION PERFORMANCE PARAMETERS

The thermal and total fusion gain can be defined as:

$$Q_{th}^{P} = \frac{P_{DT}^{th}}{P_{Loss}^{th} - P_{\alpha abs}^{th}} \text{ and } Q_{tot}^{P} = \frac{P_{DT}}{P_{Loss}^{th} + P_{Loss}^{rot} + P_{Loss}^{fast} - P_{\alpha abs}^{tot}}$$

where P_{DT}^{th} and P_{DT} are the thermal and total fusion power. The thermal loss power is $P_{abs}^{th} + P_{\alpha,abs}^{tot} - dW^{th}/dt$; rotation and fast particle components of the loss power are defined analogously. Alpha particle slowing down is also taken into account. The value of the instantaneous power gain is $Q_{IN} = P_{DT} / P_{IN}$.

It is found that Q_{tot}^{P} increases with plasma current and is similar for NB+ICRH and NB only discharges. In the record fusion pulse at 4.2 MA/ 3.6 T (Fig. 3) Q_{tot}^{P} and Q_{th}^{P} initially increase rapidly, then remain fairly constant, thus suggesting that fusion power and losses change in proportion. With the appearance of MHD activity, clearly seen in the D_α trace, both Q_{tot}^{P} and Q_{th}^{P} decrease together with the global and thermal confinement times. On the other hand, the value of Q_{IN} increases monotonically with time up to the Giant ELM. These observations may indicate that the MHD activity in the ELM-free Hot-Ion regime affects plasma losses more than neutron rate or core conditions. All the DT pulses have been limited by MHD events. However, were it possible to maintain the same confinement quality, $W_{TOT}^{2} / P_{LOSS}^{TOT}$, and the same reactivity P_{DT} / W_{TOT}^{2} into steady-state, one would expect the value of Q_{IN} to approach the measured value of Q_{tot}^{P} .

An overview of the local fusion performance and the input power profiles, as computed by the TRANSP code, is given in Fig. 4 for the record fusion pulse just before the MHD activity appears. The data show that, in the core, the fusion power density is of the same order or slightly in excess of the input power density to the thermal component from external sources, ~ 0.6 MW/m^3. At the same time, the source fusion alpha particle power density is ~ 0.08 MW/m^3, of which ~ 0.06 MW/m^3 is coupled to the electrons; this is comparable to each of the other electron heating sources, including ion-electron equipartition and change dW_e/dt in electron energy density.

5. SUMMARY AND CONCLUSIONS

Experiments in the ELM-free Hot-Ion H-mode regime have been carried out in Deuterium-Tritium plasmas in JET. Initial experiments undertaken at constant NB power, around 11 MW, demonstrated that core fuelling was dominated by wall/target recycling rather than NB fuelling; as a consequence an optimum core DT mix could be arranged by adjusting the DT mix in wall/target, gas and NB. Modelling of particle transport in discharges with different fractions of T beams into a deuterium plasma has been carried out with the transport code TRANSP.

High power experiments at 4.2 MA / 3.6 T have successfully and reliably delivered DT fusion power up to 16.1 MW and W_{DIA} of 17 MJ, and the results are consistent with extrapolations carried out with the TRANSP and JETTO codes on the basis of deuterium discharges. There are indications of isotope effects local confinement in the core and in edge transport barrier region, but the net effect on global confinement is small within the uncertainties of the analysis. Transiently, values of Q_{tot} around 0.9 ± 0.1 were achieved, consistent with values of $n_{DT}(0)\,\tau_E\,T_i(0) \sim 9 \times 10^{20}$ m^{-3} s keV. The ratio of fusion power to input power Q_{IN} is in excess of 0.6. In all cases, the high performance phase was transient, limited by external kink modes and ELMs in a similar manner to DD ELM-free H-modes. Power step-down experiments carried out in DD would suggest that $Q_{IN} \sim Q_{tot}^{P}$ might be sustained for a confinement time, but even here the performance is ultimately limited by edge stability.

It is encouraging to find regimes, such as the Hot-Ion ELM-free H-mode, where the fusion performance can significantly exceed the baseline steady state ELMy H-mode, and such plasmas find ready application in studies of particle and energy transport, alpha particle [7] and ICRF heating and TAE stability. The transient nature of this regime, however, prevents direct application of these results to a fusion reactor unless means are found of controlling the steep edge gradients, and the resulting edge MHD activity.

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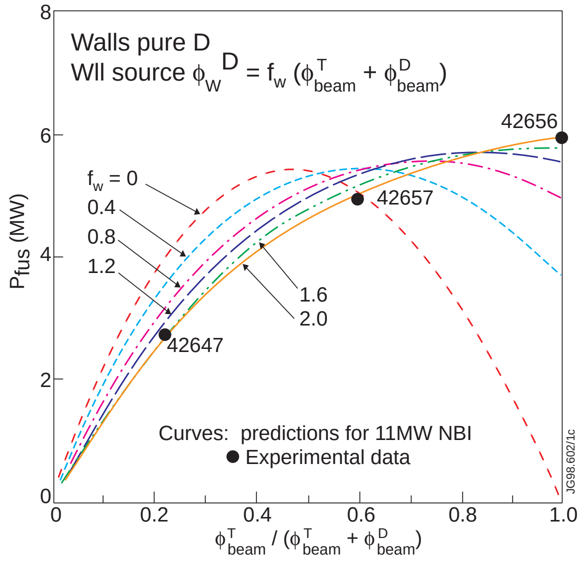

Fig. 1 : predicted and achieved fusion power P_{DT} for ELM-free Hot-Ion H-modes with ~ 11 MW NBI only, as function of beam DT mix and recycling parameter f_W.

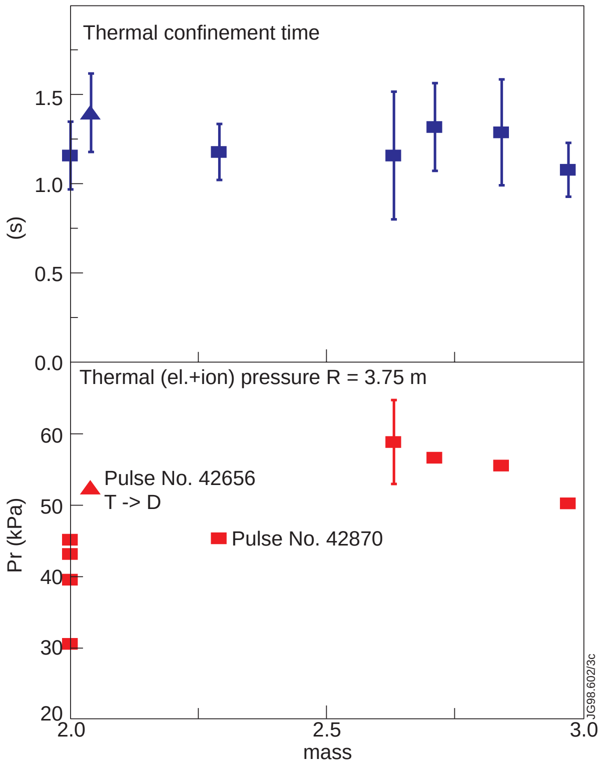

Fig. 2 : total thermal confinement τ_E and thermal pressure, at R=3.75 m, as function of edge isotopic composition. ELM-free Hot-Ion H-modes with ~ 10-11 MW NBI only.

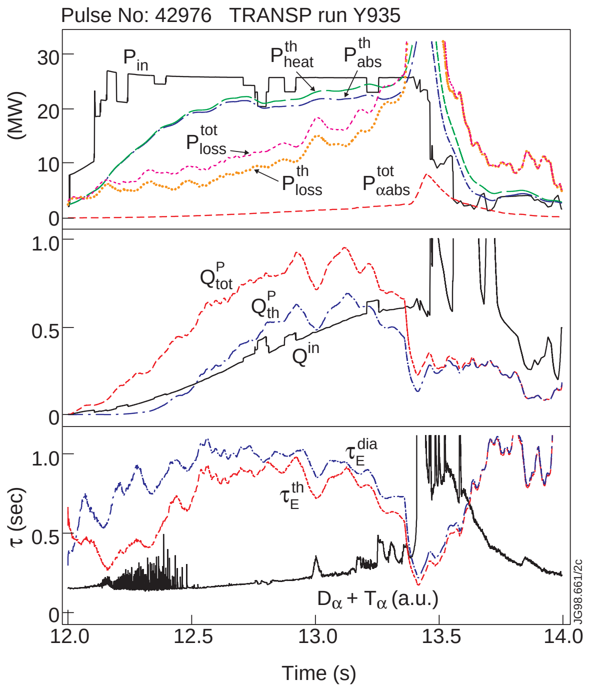

Fig. 3 : TRANSP : time dependent performance and confinement analysis for Pulse No. 42976. $P^{th}{}_{abs}$ and $P^{th}{}_{heat}$ are the power from external sources and the total power, ext. + alpha, absorbed by the thermal plasma.

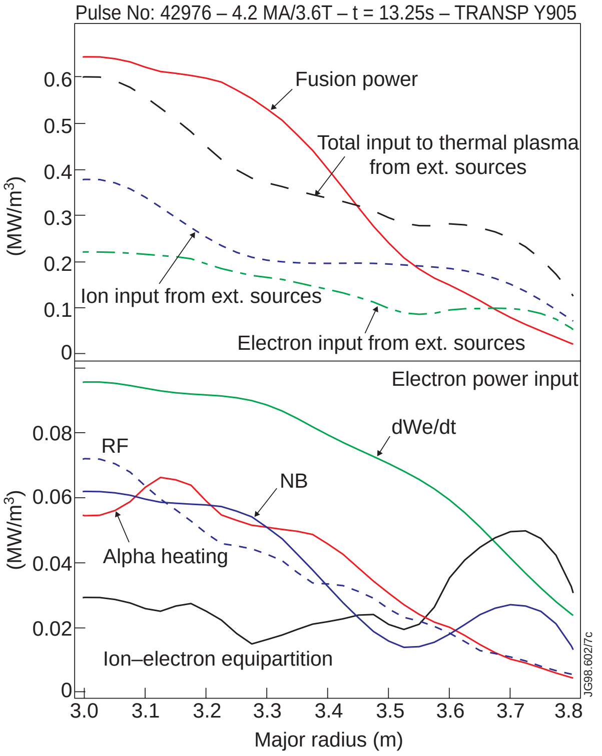

Fig. 4 : Fig. 3 : TRANSP input to thermal plasma, fusion and alpha particle heating profiles for #42976 at t = 13.25s