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High D-T Fusion Performance in ELM-free H-modes in JET

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INTRODUCTION

During the MKII Divertor campaign the performance characteristics of the Hot-Ion ELM-free H-mode regime in Deuterium plasmas have been comprehensively explored [1,2]. Experiments were carried out up to a plasma current of 4.2 MA and a toroidal field of 3.8 T, with Neutral Beam (NB) heating alone and with NB plus Hydrogen minority Ion Cyclotron Resonance Heating (ICRH), up to a total input power of about 25 MW.

The maximum fusion reactivity is obtained transiently; density and stored energy rise continuously with time, until the terminating MHD event, which is either a large sawtooth, a Giant ELM or an external kink mode. The identification of the so-called Outer Mode as an ideal external kink, driven by the edge current gradient, led to the development of a method for its mitigation or avoidance by decreasing the plasma current during the ELM-free phase. As a result the performance, robustness and reliability of the regime have been improved, extending the maximum DD neutron yield to 5.2×10^{16} s^{-1} at 3.8 MA/3.4 T with combined NB+ICRH, thereby making the regime an ideal candidate for high performance experiments in DT.

OVERVIEW OF THE HIGH POWER HOT-ION ELM-FREE EXPERIMENTS

The DT experiments in the Hot-Ion ELM-free were carried out first in the standard 3.8 MA / 3.4 T scenario. Preliminary experiments at constant NB power [3], around 11 MW, indicated that the optimum core DT mix could be achieved by adjusting the DT mix in wall/target, gas and NB. The scenario for the high power discharges included, as did the DD experiments, a current ramp-down of ~ 0.2 MA/s to mitigate the Outer Mode and a DT continuous gas bleed. One of the NB systems was converted to inject 100% Tritium at up to 155 kV energy, making the total NB power available in excess of 22 MW, higher than in the DD campaign.

The first high power experiments were carried out both with NBI alone and with NBI + ICRH, using (H)DT heating, and allow a direct comparison of actual DT performance with extrapolations from DD discharges. The NB only case reached 12.3MW 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 in the range of 50% in the core, and the high performance phase terminated with a combination of Outer Mode and Giant ELM, although the NB pulse suffers from a large sawtooth [4]. The value of $Q_{IN}=P_{DT}/P_{IN}$ reached 0.57 in both discharges. Numerical studies of the ICRF power depositions show, for DT as well as for DD discharges [2], that up to 40% of the power can be absorbed at the $2\omega_{CD}$ resonance by bulk and NB ions, thereby increasing by 30-35% the power input to the bulk ions in the plasma core. The analysis also suggests that the non-thermal DT neutron yield, due to ICRF Deuteron acceleration, is negligible.

A second set of experiments was carried out at higher plasma current and toroidal field, 4.2 MA / 3.6 T, to exploit the expected improvement in confinement and ELM stability with plasma current. In these discharges the full NB power capability was also used, and the plasma mix was slightly biased towards Tritium, T/(D+T) ~ 0.6-0.65, to compensate for the higher flux of Deuterium from NBI. A significant gain in performance was thus achieved (fig. 1), resulting in a new record in fusion power, 16.1 MW, and stored energy, 17 MJ, for an input power of 25.7 MW corresponding to $Q_{IN} > 0.6$. 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]. No net dependence of confinement on isotopic plasma composition has been found, but there are indications of an isotope effect on the edge pressure pedestal [6].

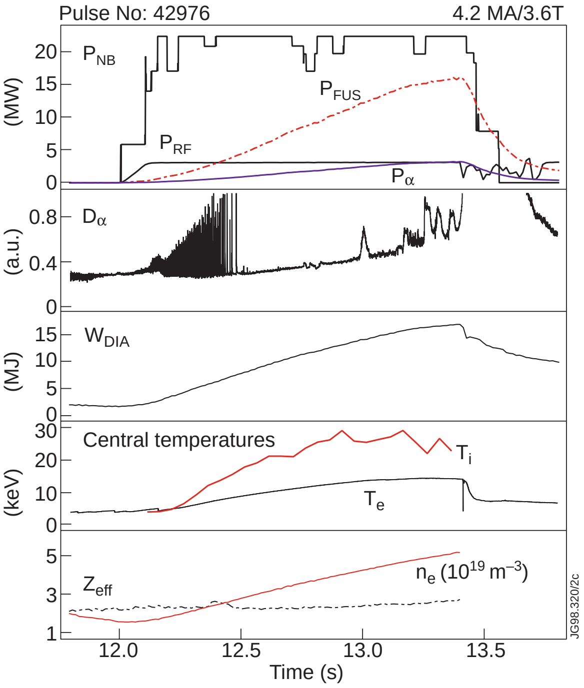


Fig. 1 : time evolution of plasma parameters for DT discharge #42976 (NB+ICRH)

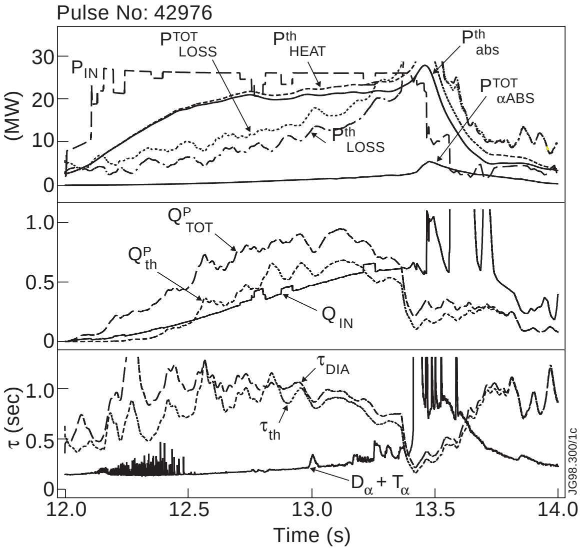
DT FUSION PERFORMANCE PARAMETERS

The thermal and total fusion gain can be defined as :

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

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.

In general, it is found that Q_{tot}^{P} is similar for NB only and NB+ICRH discharges, and it increases with plasma current. An overview of the DT fusion performance parameters for the record fusion pulse is given in fig. 2. While Q_{tot}^{P} and Q_{th}^{P} rise rapidly then remain roughly constant, suggesting that losses and fusion power change in proportion, the value of Q_{IN} increases monotonically with time. A degradation in Q_{tot}^{P}, Q_{th}^{P} and confinement time is observed at t = 13.2 s, coinciding with the appearance of MHD activity, but the value of Q_{IN} continues to increase up to the occurrence of the Giant ELM. This seems to suggest that such MHD activity affects plasma losses more than neutron rate and core conditions. However, all the DT pulses have been limited by MHD events and it is therefore impossible to deduce how Q^{P}_{tot} and Q^{P}_{th} would evolve relative to Q_{IN} in case of approach to steady-state.



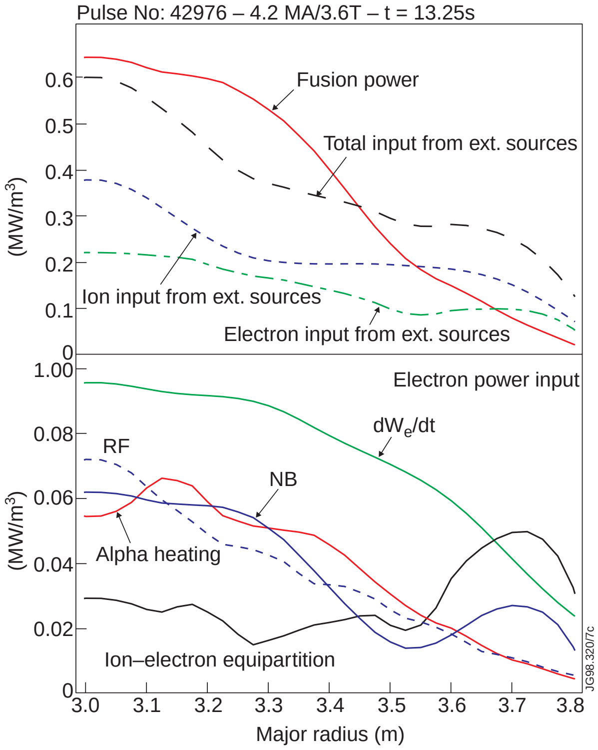


Fig. 2 : TRANSP : time dependent performance and confinement analysis for Pulse No. 42976. P^{th}_{abs} and P^{th}_{heat} are the power from external sources and the total power, ext. + alpha, absorbed by the thermal plasma.

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

LOCAL FUSION PERFORMANCE AND ALPHA PARTICLE HEATING

An overview of the local fusion performance and the input power profiles, as computed by the TRANSP code, is given in fig. 3 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 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. A series of experiments dedicated to the study of alpha particle heating in the Hot-Ion ELM-free regime is presented in [7].

SUMMARY AND CONCLUSIONS

Hot-Ion ELM-free H-modes in DT plasmas have successfully and reliably delivered P_{DT} up to 16.1 MW and W_{DIA} of 17 MJ. The results are in good agreement with extrapolations, carried out with TRANSP & JETTO codes, from similar Deuterium discharges. Transiently, values of Q_{tot}^{P} around 0.9 were achieved, consistent with values of $n_{DT}(0)\ \tau_E\ Ti(0) \sim 9 \times 10^{20}\ m^{-3}$ s keV. The ratio of fusion power to input power Q_{IN} is in excess of 0.6. The data suggest an isotope effect on the edge pressure pedestal, though no net dependence of global confinement on the isotopic plasma composition has been found.

The transient nature of this regime prevents direct application of these results to a fusion reactor. This would require control of the pedestal to avoid the edge stability limits. Nevertheless, it is highly satisfying that the understanding of the regime is sufficient to improve the fusion performance by such a significant margin, and as such provides an excellent vehicle for alpha particle studies in JET and, possibly, a transient approach to ignition in a larger device. Most importantly, these experiments have not encountered unexpected obstacles to the realisation of fusion performance in DT. Taken together with the clear observation of alpha particle heating [7], these results are a positive encouragement to efforts towards a next step.

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