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# Effect of $D_2$ fuelling location in JET MkII Gas Box divertor discharges

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## 1. Introduction

The MarkII Gas Box (MkII-GB) divertor is the latest in a series of divertor designs explored at JET. The geometrical closure of the divertor has been increased in each version, from the open MarkI structure, to the more closed MarkIIA and MarkIIAP [1-3], to the present MarkII-GB. In addition, in the MkII-GB divertor a septum is located at the centre of the divertor chamber (Fig. 1). The septum was designed to separate the recycling neutrals between the divertor legs. In order to test this, we have conducted dedicated experiments, in which we have varied the poloidal location of $D_2$ fuelling into L-mode and steady state ELMy H-mode plasmas.

The large majority of the discharges carried out with the GB divertor were in vertical configuration (strike zones on the vertical targets), but comparisons with plasmas in corner configuration (strike zones in the corner of the divertor target) were also established. In this paper they will be referred to as V/SFE/LT and C/SFE/LT configurations, respectively, where V, C = vertical, corner, SFE = standard flux expansion, LT = low triangularity ($\delta \sim 0.22$ in the L-mode discharges and $\delta \sim 0.25$ in the H-mode discharges).

## 2. Effect of $D_2$ fuelling location in L-mode density limit discharges

$D_2$ was injected from the inner or outer divertor, as shown in Fig. 1, or from the outer midplane into NBI or ICRH heated discharges ($P_{IN}$ = 2MW, in addition to the Ohmic power), with $I_P$ = 2 MA, $B_T$ = 2.5 T. The gas fuelling rate was raised steadily until the density limit disruption. The experimental results are summarized as follows:

a) The fuelling efficiency varies considerably with fuelling location: it is highest when fuelling from the outer midplane and lowest when fuelling from the outer divertor. For the L-mode density limit discharges in MkII-GB, deuterium fuelling rates $\Phi_D \sim 2.5 \times 10^{22}$ atoms/s are required for the plasma to reach the density limit when fuelling from the outer midplane, while $\Phi_D = 3.5 - 4 \times 10^{22}$ atoms/s with inner divertor fuelling and $\Phi_D = 6 - 7 \times 10^{22}$ atoms/s with outer divertor fuelling (all discharges had divertor cryopumping, with an estimated pumping speed, in vacuum, of $S_P = 110\ m^3/s$).

b) The fuelling location affects strongly the in/out asymmetry of divertor detachment and this effect is more pronounced in corner than in vertical target configurations. With inner divertor fuelling, inner divertor detachment begins at lower upstream densities, with outer fuelling detachment in the inner divertor leg is delayed and the evolution of the ion fluxes to inner and outer target is approximately symmetric.

c) The density limit, just before the plasma disruption, does not depend on the fuelling location (within the 10% reproducibility of the measurements). This is consistent with the observation that the density limit coincides with complete plasma detachment at the inner divertor leg [4], which occurs at the same density for inner and outer divertor fuelling.

Points b) and c) are illustrated in Fig. 2, showing the effect of fuelling location on divertor plasma detachment and on the density limit in two C/SFE/LT discharges with inner and outer divertor fuelling.

2D divertor transport simulations of the density limit discharges with the EDGE2D/NIMBUS codes reproduce the trends of in/out detachment asymmetry found experimentally. In particular, the increase in neutral pressure at the divertor cryopump with density is reproduced, as well as the ion fluxes to the divertor targets, measured by Langmuir probes, both in shape and magnitude. In the simulation of the discharge with corner configuration and inner divertor fuelling, at high density, removing the septum reduces the strong in/out divertor detachment asymmetry.

## 3. Effect of $D_2$ fuelling location in steady state ELMy H-modes

In JET, ELMy H-modes fuelled with NBI only (without additional gas fuelling) achieve in steady state a 'natural density' $n_e/n_{GDL}$ ~ 50% (where $n_e$ is the central line averaged density and $n_{GDL}$ is the Greenwald density limit). There is some variation in this value with plasma current and plasma triangularity. By adding gas fuelling, the density of steady state ELMy H-modes can be increased up to $n_e/n_{GDL}$ ~ 70-80%, but at high fuelling rates high density is obtained at the price of degradation of the energy confinement. As the fuelling rate is increased at constant input power, the ELM frequency increases and the ELM amplitude decreases until a transition from Type I to Type III ELMs occurs. With increasing fuelling rate the density first saturates and then even decreases. A back transition from H- into L-mode may take place.

In the experiments reported here, $D_2$ was injected at constant rate (but with increasing rate from pulse to pulse) from the inner or outer divertor SOL into NBI fuelled ($P_{NBI}$ ~ 12 MW) steady state ELMy H-modes ($I_P$ = 2.5 MA, $B_T$ = 2.4 T, $\delta$ ~ 0.25). Fuelling from the outer midplane is also possible, but could not be used at medium to high fuelling rates due to technical problems with high local pressure in the NB ducts.

At high fuelling rates, $\Phi_D > 3 \times 10^{22}$ atoms/s, the plasma thermal stored energy degrades more with inner divertor fuelling, for the same fuelling rate (Fig. 3). This effect is more pronounced in corner than in vertical target configuration discharges. The experiment also shows that the maximum density achieved in ELMy H-modes does not depend on the fuelling location in JET MkII-GB.

At moderate to high fuelling rates, the fuelling location affects the ELM characteristics of the discharge: the ELM frequency is higher with inner divertor fuelling, for the same fuelling rate (Fig. 4). The electron and ion temperatures at the top of the pedestal, $T_{e,PED}$ (measured with the ECE heterodyne radiometer) and $T_{i,PED}$ (measured with charge exchange recombination spectroscopy), as well as the pedestal pressure, are lower with inner fuelling, compared with outer divertor fuelling. This indicates that the Type I to Type III ELM threshold is affected by the fuelling location. In fact, the discharges with high inner fuelling are in the Type III ELM regime and $T_{e,PED}$ is ~ 500 eV. In contrast, even at the maximum outer divertor fuelling rate achieved (> than the inner fuelling rate) the discharge is in the Type I ELM regime and $T_{e,PED}$ ~ 700 eV, consistent with a $T_{e,PED}$ boundary between Type I and Type III ELMs of 500 – 700 eV (at 12 MW of NBI heating and $I_P$ = 2.5 MA, $B_T$ = 2.4 T). Since in JET the pedestal pressure is seen to scale with the thermal Larmor radius ($p_{PED} \propto (T_{PED})^{1/2}$) [5], the degradation in pedestal energy is larger with inner than outer fuelling, for the same fuelling rates, as shown in Fig. 5 for the V/SFE/LT discharges. Here the pedestal energy is $W_{PED} = 3/2 \langle p_{PED} \rangle V_P$, with $V_P$ the plasma volume inside the last closed flux surface and $\langle p_{PED} \rangle$ the time averaged (over several energy confinement times) plasma pressure at the top of the pedestal ($p_{PED} = p_{i,PED} + p_{e,PED} = 2\, n_e T_e$, where $n_i \sim n_e$ and $T_i \sim T_e$ have been used, consistent with measurements). Note that the pedestal energy degradation alone cannot explain the degradation in total thermal stored energy, and that some degradation in the core stored energy is also observed, as reported earlier [5].

In contrast to the L-mode case, there appears to be no change in in/out asymmetry of ion fluxes to the divertor targets when changing the fuelling location, both at low and high fuelling rates. In addition, ratios of $D_\gamma$ to $D_\alpha$ radial profiles across the divertor, measured with a CCD camera which views the divertor chamber from the top of the tokamak, show no evidence of recombination in these discharges.

## 4. Conclusions

Experiments have been conducted in JET with the MkII-GB divertor to study the effect of $D_2$ fuelling from different poloidal locations of the vessel into L-mode and steady state ELMy H-mode discharges.

In L-mode density limit discharges the fuelling efficiency varies considerably with fuelling location, being highest when fuelling from the outer midplane and lowest with outer divertor fuelling. The fuelling location affects strongly the in/out asymmetry of divertor detachment. The density limit does not depend on the fuelling location, consistent with the density limit occurring at complete plasma detachment at the inner divertor leg. These results are qualitatively reproduced by EDGE2D/NIMBUS simulations. When the septum is removed in the simulation with corner configuration and inner divertor fuelling at high density, the strong inner/outer divertor detachment asymmetry is reduced.

The dominant effect of the fuelling location in steady state ELMy H-modes is the change in fuelling efficiency and thus of edge temperature and ELM characteristics of the discharge. The ELM frequency increases and the pedestal stored energy degrades more with inner divertor fuelling, for the same fuelling rate. Some degradation of the core plasma stored energy is also observed at high fuelling rates, in agreement with previous measurements in JET. The maximum density achieved in ELMy H-modes is found to be independent of the $D_2$ fuelling location. There appears to be no correlation with divertor detachment when changing the fuelling location, since no change in in/out asymmetry of the ion fluxes to the divertor targets is measured when changing the fuelling location, in contrast to the L-mode case, nor is there evidence of recombination from line-of-sight integrated $D_\gamma$ / $D_\alpha$ profiles across the divertor.

**References:**
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[3] G. M. McCracken et al., Nucl. Fusion **39** (1999) 41.
[4] C. F. Maggi et al., 'The isotope effect on the L-mode density limit in JET H, D and T divertor plasmas', accepted for publication in Nucl. Fusion.
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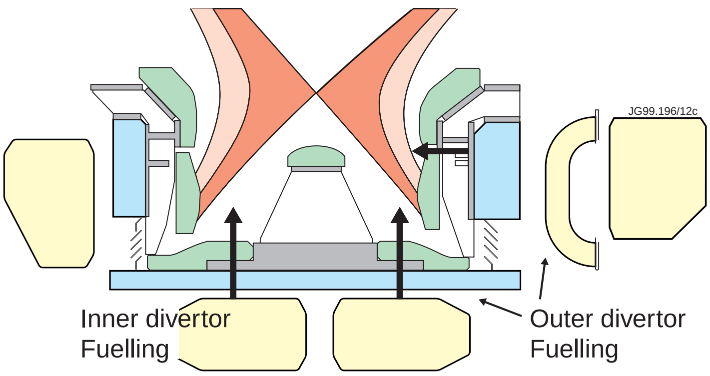


**Figure 1.** Cross section of the MarkII GB divertor, with the location of the divertor gas injection modules used in the L-mode density limit experiments.

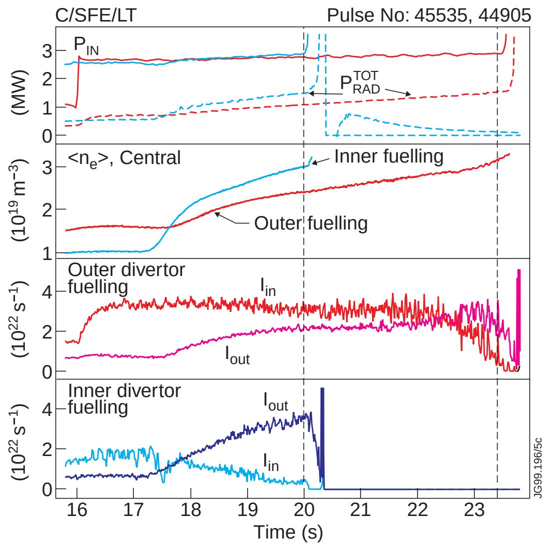


**Figure 2.** C/SFE/LT L-mode density limit pulses, showing the effect of $D_2$ fuelling location on the density limit and on the in/out asymmetry of divertor detachment, as measured by the total ion flux to inner and outer divertor target. The vertical dashed lines mark the density limit prior to plasma disruption.

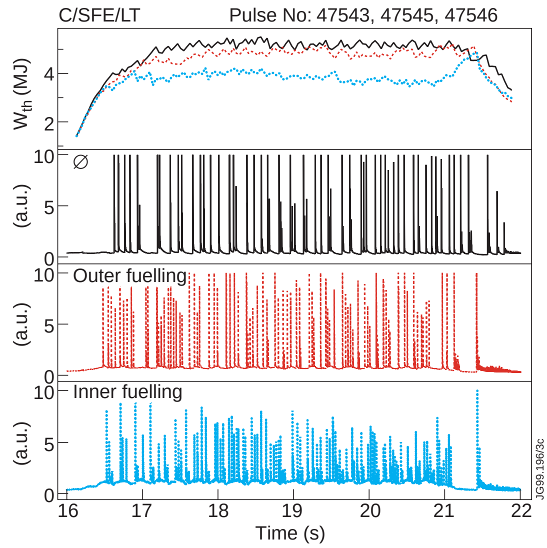


**Figure 4.** Time evolution of the total thermal stored energy and ELM characteristics, measured by fast $D_\alpha$, for three ELMy H-modes ($P_{NBI}$ = 12 MW, corner configuration) with no $D_2$ fuelling, outer and inner divertor fuelling ($\Phi_D = 3.6 \times 10^{22}$ atoms/s).

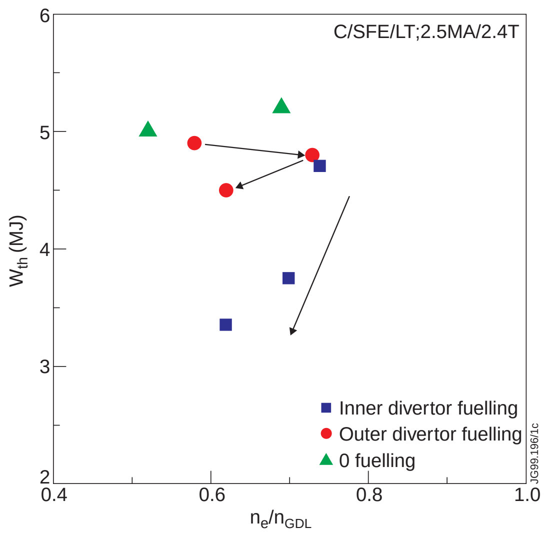


**Figure 3.** Total thermal stored energy versus fraction of the Greenwald density limit for steady state ELMy H-modes in the corner configuration, with varying $D_2$ fuelling location. The arrows indicate the direction of increasing $D_2$ fuelling rate.

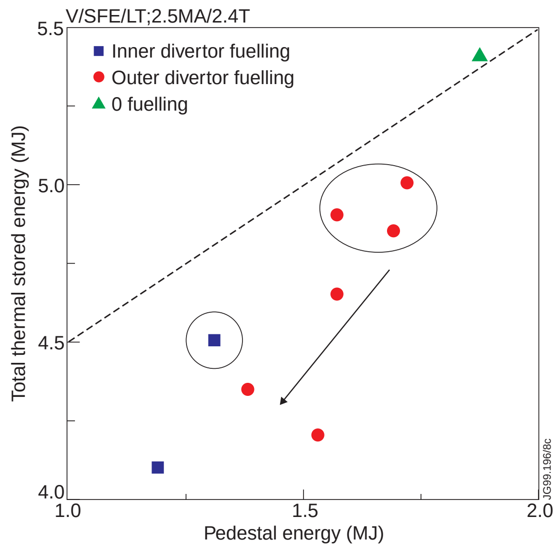


**Figure 5.** Total thermal stored energy versus pedestal energy for the ELMy H-modes with vertical configuration. The dashed line indicates the degradation of total stored energy that would occur if it were due only to degradation of pedestal energy. The circles group pulses with similar fuelling rates, for comparison.