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Neutral particle retention in the JET MK I divertor

J.K. Ehrenberg *, D.J. Campbell, P.J. Harbour, L.D. Horton, A. Loarte, G.K. McCormick, R.D. Monk, G.R. Saibene, R. Simonini, A. Taroni, M.F. Stamp

JET Joint Undertaking, Abingdon, Oxfordshire OXI4 3EA, UK

Abstract

Retention of neutral deuterium and nitrogen in the JET MK I divertor has been investigated. Results show that ohmic plasma detachment reduces deuterium retention, that the magnetic divertor configuration has some influence on the achievable deuterium retention, and that nitrogen in nitrogen-seeded steady state detached H-mode discharges accumulates in the divertor.

Keywords: JET; Divertor plasma; Plasma detachment; Neutral confinement and transport; Impurity transport

1. Introduction

Escape of neutral deuterium and impurities from the divertor into the main plasma chamber is known to have a number of deleterious effects on the main plasma like an increase of the H-mode power threshold [1], a deterioration of the H-mode confinement [2], an increase of the main chamber wall sputtering and the plasma impurity concentration. Hence, the study of neutral particle retention promises valuable information with relevance to improving the main plasma performance. Since the restart of the experimental programme of JET in 1994, a major part of the experimental activities has been centred around the question which divertor geometry would best be suited to enable good neutral particle retention of deuterium as well as of impurities, particularly of those seeded into the discharge in order to obtain a radiating divertor plasma. Experiments were carried out to characterise this retention capability in a number of discharges with different magnetic configurations and in different confinement regimes. Results reported here are from the MK I divertor, see Fig. 1, the first in a series of several divertors that will be tested in JET.

* Corresponding author. Tel.: +44-1235 528822; fax: +44-1235 464766; e-mail:jke@jet.uk.

2. Experimental methods

Two methods were employed to measure neutral particle fluxes:

(i) Direct measurements by using ASDEX-type hot cathode ion gauges [3]. They were placed in the sub-divertor volume beneath the divertor target plates as well as outside the divertor at the inner wall (Fig. 2). All sub-divertor data presented here were obtained from a gauge that was located just in front of the divertor cryo-pump, with the gas inlet opening oriented towards the divertor target structure. Because of technical reasons only the sub-divertor gauges were calibrated by controlled deuterium gas puffs into the torus without the cryo-pump in operation. The inner wall gauge was only used for qualitative cross-checks with the measured D_α photon flux at the inner wall. Ion gauges measure directly particle fluxes. Pressure and densities can be derived assuming isotropic conditions and an average ambient temperature (assumed to be only 323 K in the sub-divertor volume, compared to 573 K at the main vessel wall, owing to the presence of a number of cooled structures in the sub-divertor volume like the cryo-pump chevrons, a water baffle, and the divertor coils). Neutral particle measurements by ion gauges do not explicitly distinguish between different particle species. In discharges that were not seeded with impurities ($Z_{eff} \approx 1.5$) it was assumed that the majority of neutral particle fluxes

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were deuterium fluxes. In discharges with nitrogen seeding, deuterium and nitrogen components, respectively, were separated by a special procedure of analysis where the ion gauge flux, $\Gamma_{n,\text{ion gauge}}$, was compared with the total (sum of inner and outer) divertor D_α photon intensities, $I_{\alpha,\text{div}}$. For a given magnetic divertor configuration in non-nitrogen seeded discharges the ratio between the two signals, i.e. $\Gamma_{n,\text{ion gauge}}/I_{\alpha,\text{div}}$, is constant within about 20%, almost independent of the plasma density and power, even during plasma detachment. In nitrogen seeded discharges of the same configuration the expected neutral deuterium sub-divertor flux was then derived from the measured divertor D_α photon intensities. Using the ASDEX-gauge measurements the nitrogen flux component was then calculated by taking into account the different ionisation probabilities of deuterium and nitrogen (2.5 times that of deuterium) and assuming equal temperatures of the neutral gases outside the gauge. This method tends to underestimate the nitrogen content as the specific D_α photon flux in nitrogen seeded discharges could have been enhanced due to a larger electron density in the divertor compared to that in similar but nitrogen-free discharges. It is estimated that this would result in about a factor of two or less overall uncertainty of the neutral nitrogen to deuterium ratio.

(ii) Indirect measurements of the neutrals entering the main plasma boundary were made by recording radial D_α photon fluxes, I_α, at three different poloidal locations in the main plasma chamber as indicated in Fig. 2. This intensity translates into a neutral flux into the plasma boundary, $\Gamma_n = 4\pi I_\alpha S$, where S is the inverse photon efficiency (assumed to be 20). Above an electron temperature of 20 eV, likely to be exceeded at the main plasma separatrix, this factor is almost independent of the electron temperature.

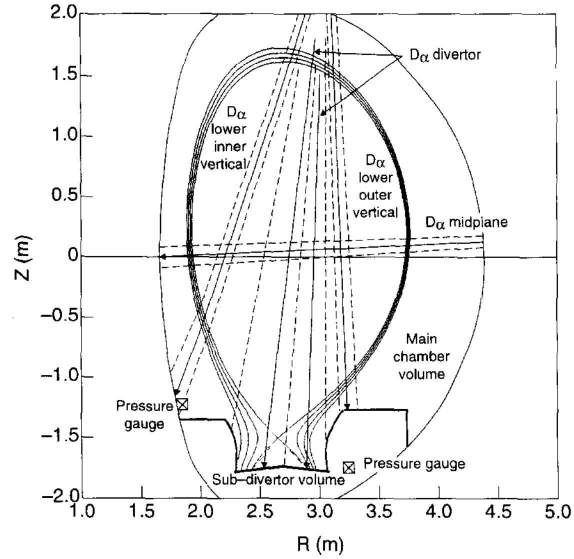

Fig. 2. Overview of neutral particle diagnostics in JET.

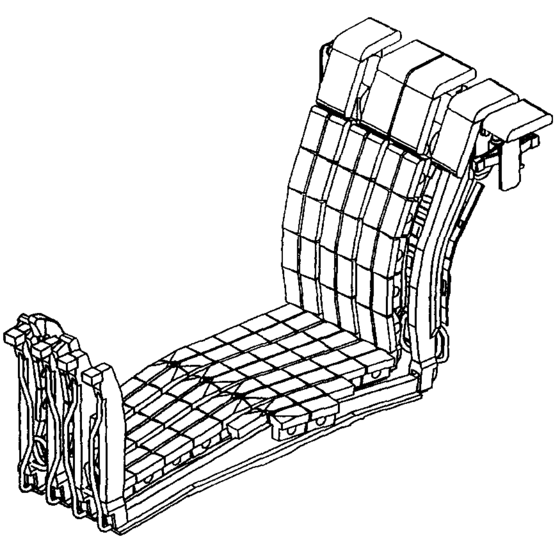

Fig. 1. A module of the JET MK I divertor showing the target tile arrangement (horizontal and vertical) and the interspaces which allow neutral gas to enter the sub-divertor volume (see Fig. 2).

The capacity of the divertor to retain neutral particles is expressed in terms of flux and concentration ratios. For deuterium, there are three neutral flux ratios, i.e. the ratio between the sub-divertor neutral deuterium flux and the neutral deuterium fluxes at each of the three different poloidal locations in the main plasma chamber as given in Fig. 2. The retention of nitrogen is expressed by a nitrogen concentration ratio or enrichment factor. This is defined as the ratio of the neutral nitrogen concentration (relative to deuterium) in the sub-divertor volume divided by the nitrogen concentration (relative to deuterons) in the core plasma. The latter is derived from Z_{eff} data and represents an upper limit as other impurities like carbon and beryllium are neglected.

3. Experimental results

3.1. Deuterium retention in detached ohmic discharges

A density ramp was performed in discharge #35430 to attain plasma detachment from the horizontal target plates of the JET divertor. The begin of plasma detachment is defined as the begin of the roll-over of the ion saturation current on the target plates [4]. Fig. 3 shows the three deuterium flux ratios as a function of line average core plasma density. This characteristic change of these ratios with density is also observed by the ratio of the subdivertor pressure gauge signal to the signal of the uncalibrated inner wall ASDEX gauge (see Fig. 3). This strongly suggests that during the density ramp there is no sizeable

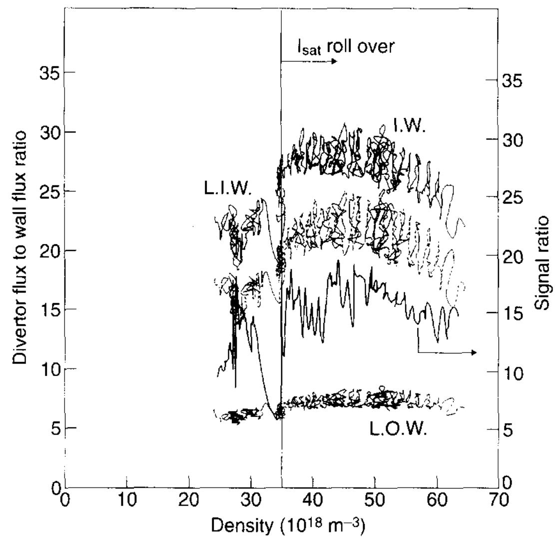

Fig. 3. Neutral deuterium flux ratios as a function of central line average density for #35430 (2 MA, 2.4 T): I.W. = horizontal viewing line; L.I.W. = lower inner wall viewing line; L.O.W. = lower outer wall viewing line (see also Fig. 2). Also given is the raw signal ratio of the subdivertor pressure gauge and inner wall pressure gauge.

variation of the specific D_α photon efficiency in the plasma boundary.

Fig. 3 indicates the existence of three different density regimes in ohmic discharges where, respectively, the flux ratios increase, then saturate, approximately coinciding with the onset of plasma detachment, and then decrease. The relative differences between the flux ratios are consistent with the expected relative differences between neutral deuterium fluxes in the main chamber, being larger closer to the divertor. During the density ramp it is observed that the photon flux of carbon III (465 nm) and beryllium II (527 nm) lines in the main plasma boundary (horizontal line of sights) increase with density, whereas they decrease in the divertor plasma. The plasma's Z_{eff} decreases from an already low starting value of 1.2 to a value of 1.

3.2. Deuterium and nitrogen retention in steady state ELMy H-mode discharges

In discharge 33204 (2.5 MA, 2.4 T) with similar divertor configuration as in the discharge described in Section 3.1 a steady state ELMy H-mode was seeded with nitrogen to establish detachment with a radiative divertor plasma. Total radiation losses reached 80% of the total input power of 14.3 MW. The nitrogen fluxes and concentrations are given in Fig. 4. Nitrogen puffed into the discharge mainly accumulates in the divertor. The nitrogen enrichment is about 30 which, as mentioned in Section 2 is at a lower limit. The deuterium flux ratio is of the same order or even higher as in attached ohmic discharges. For the plasma midplane the deuterium flux ratio is around 50.

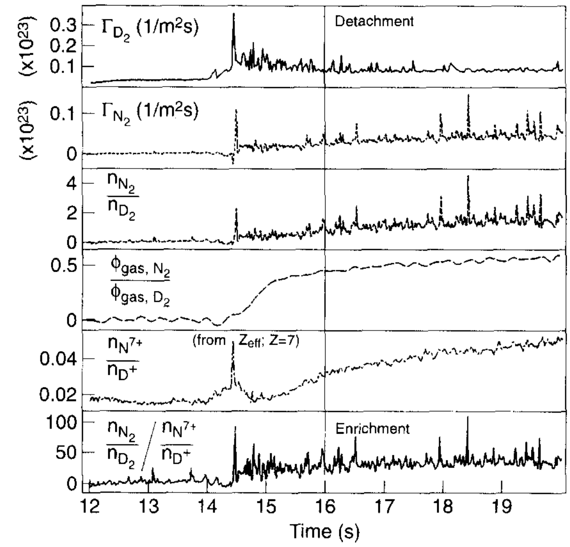

Fig. 4. Sub-divertor neutral nitrogen and deuterium fluxes and density ratio of a detached H-mode discharge (#33204, 2.5 MA, 2.5 T) with 14 MW of neutral beam and ohmic heating power. The core plasma nitrogen to deuterium density ratio was derived from Z_{eff} data.

3.3. Deuterium retention in horizontal and vertical divertor target configuration

Target configuration experiments were carried out by sweeping the plasma strike zone from the horizontal targets to the vertical targets within about 6 s of an ohmic discharge, see Fig. 5. The line average density was kept

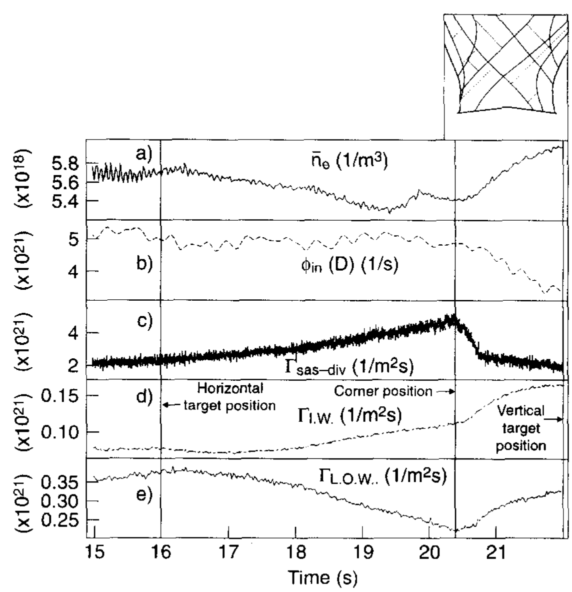

Fig. 5. Plasma parameters and neutral deuterium fluxes in #31725 (2 MA, 2.8 T), indicating times with characteristically different positions of the plasma strike zone in the divertor.

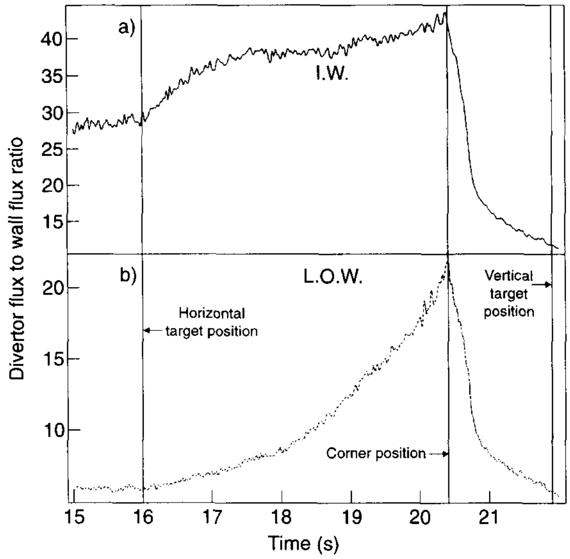

Fig. 6. Deuterium flux ratios for various positions of the separatrix in the divertor module.

constant within less than 10% by feedback control of the gas feed system. The largest sub-divertor neutral deuterium flux and the largest flux ratio is measured when the separatrix is in the corner between horizontal and vertical target plates (Fig. 6). The presence of a toroidally continuous gap between the vertical and the horizontal target tiles allows this configuration to provide an increased conductance for neutral particles to go through the divertor structure into the sub-volume. The main chamber neutral deuterium fluxes at the plasma midplane also increase somewhat, indicating a larger escape fraction of neutrals. The lower outer wall neutral flux, however, decreases. This is yet not well understood. Close to the divertor a rather large neutral particle density gradient is likely to be present and changes of magnetic configuration can therefore strongly affect the measured D_α-intensity, even without a change of the amount of neutrals escaping from the divertor. When the plasma is in vertical target configuration the sub-divertor flux is decreased by a factor of 2, while the main chamber fluxes increase. Therefore, this configuration shows the lowest neutral particle flux ratio.

3.4. Deuterium retention at different magnetic flux expansions in the divertor

A wider plasma scrape-off layer at the target plates is theoretically expected to reduce the neutral particle escape into the main plasma chamber by increased ionisation (plugging). However the flux ratios as a function of line average density show no significant differences to the standard configuration, Fig. 7. Only the lower outer vertical line of sight suggests a somewhat lower flux ratio, but here again potentially large neutral density gradients make results difficult to interpret. However, at high magnetic flux expansions a substantial decrease of the neutral flux ratio can be observed if there is a change of the position of the separatrix as indicated in Fig. 8. Pushing the inner

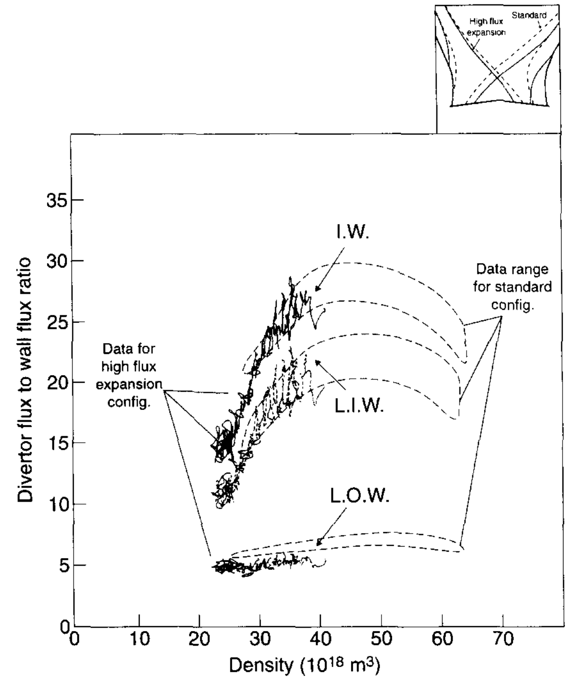

Fig. 7. Comparison of deuterium flux ratios between high and standard magnetic flux expansion in the divertor (2 MA, 2.4 T).

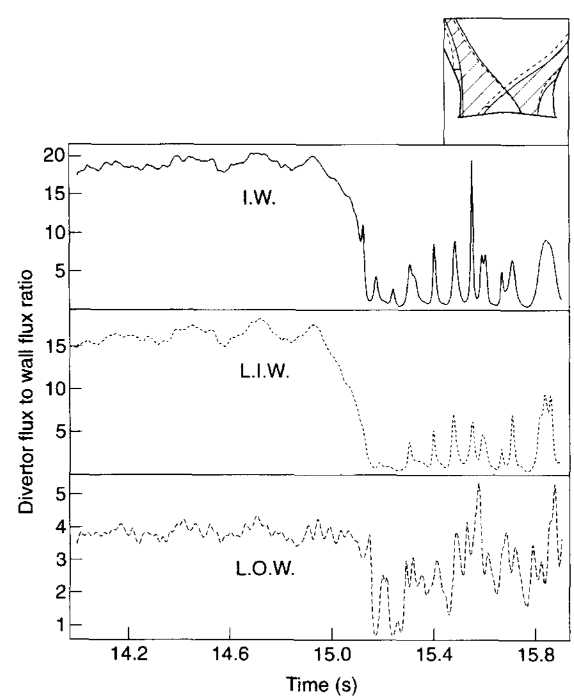

Fig. 8. Change of deuterium flux ratio by changes of the position of the separatrix at the inner divertor (2 MA, 2.4 T).

separatrix towards the inside can reduce the flux ratio by up to an order of magnitude with the result of main chamber neutral fluxes being as high as sub-divertor fluxes. During this position change the region of interception between the target tiles and the magnetic flux surface that is 3 cm away from the separatrix (measured at the outer plasma midplane) moves from the horizontal target plates to the upper vertical target plates at the inner side of the divertor.

4. Discussion of results

4.1. Neutral deuterium retention in and escape from the divertor

Neutralisation of plasma particles takes place predominantly at the divertor target plates. Because of the divertor geometry neutrals that are re-emitted from the horizontal target plates have no chance to enter directly into the sub-divertor volume. For this they need to change their direction of movement. This can be enabled by a number of atomic processes with the divertor plasma: (i) Elastic scattering of neutral atoms and molecules at cold ions. This process can become important during detached plasma phases, i.e. at low divertor plasma temperatures (< 10 eV). (ii) Dissociation of molecular deuterium into a deuteron and a deuterium atom. In a Franck–Condon dissociation process the atom can gain kinetic energy of a few eV. The same applies for charge exchange processes. If these processes take place close to the target surface, the target flux of neutrals can be larger than the neutral flux of particles escaping from the divertor plasma in the direction of the main plasma. This neutral target flux fuels the sub-divertor volume through gaps between target tiles, increasing the deuterium density until a balance is reached between the influx and the efflux. The efflux from the subdivertor is essentially composed of three parts: (i) neutrals that return into the divertor plasma through the target gaps; (ii) neutrals that escape directly into the main plasma chamber through structural leaks in the divertor module, (iii) neutrals that are pumped by the cryo-pump.

The relative importance of the leaked component can be assessed: for the case of #35430 the maximum sub-divertor pressure is $1.5 \cdot 10^{-1}$ Pa. At this pressure the Knudsen number in the sub-divertor volume is about one or less, indicating the presence of the molecular flow regime, i.e. $\Phi = PC$, where Φ is the leaked flow, P is the sub-divertor pressure and C is the effective conductance through the divertor module's structural leaks. Therefore, if the leakage dominates neutral particle losses from the divertor an increased sub-divertor pressure (or flux) should result in a proportional increase of the leaked flux and the ratio should be constant. This is not observed, as shown in Fig. 3. Consequently, the observed change of the flux ratios should, to a large degree, be due to a change of the neutrals' escape probability from the divertor plasma during the density ramp. The initial increase at lower density may be interpreted in terms of increased recycling by larger re-ionisation and better neutral retention. When detachment sets in, the electron temperature as well as the electron density of the divertor plasma at the target plate decrease, allowing a larger fraction of neutrals not to become ionised and therefore to escape. In addition the SOL decay length increases during detachment. This can lead to increased scraping of the SOL plasma at the divertor baffle plates bringing the neutral recycling closer to the main plasma, thus contributing to the decrease of the flux ratios.

The decrease of deuterium flux ratios after an inward shift of the divertor plasma separatrix is interpreted as a consequence of such an enhanced SOL-plasma scraping at baffle plates (the vertical target plates). Generally, configurations with high magnetic flux expansion are more prone to be affected by SOL plasma scraping at baffle plates. It is rather critical where exactly the SOL plasma resides on the vertical target plates. If the SOL plasma reaches the horizontal parts of the upper vertical target plates, recycling neutrals are scattered away from the separatrix towards the main plasma. This interpretation is consistent with the observation that the highest flux ratio and lowest main chamber neutral particle fluxes are reached with the divertor plasma in the corner position, a configuration that allows relative effective neutral particle baffling.

4.2. Nitrogen retention

It was outlined in Section 2 that the derived nitrogen concentration in the plasma is at an upper limit whereas the nitrogen concentration in the divertor neutral gas is at a lower limit. It is interesting to assess the possible nitrogen concentration in the divertor plasma as opposed to that in the divertor neutral gas. A proper treatment of this problem needs elaborate code calculation which is beyond the scope of this paper. In the high recycling as well as in the detached plasma regime the deuterium ionisation rate can be expected to be larger than the inflow of plasma deuterons along the SOL and thus controls the divertor ion density. Ionisation of deuterium as well as nitrogen in the divertor plasma must be balanced by the ion efflux from the divertor plasma. From the ratio of the flow balance equations for deuterium and nitrogen one obtains for the divertor plasma density ratio:

$$\frac{n_{N_+}}{n_{D_+}} = \frac{n_{N_0}}{n_{D_0}} \frac{V_{N_0}}{V_{D_0}} \frac{V_{D_+}}{V_{N_+}} \frac{f_N}{f_D}$$

where the V's stand for the flow velocity of the neutral particles (subscript 0) and the charged panicles (subscript +) of nitrogen (N) and deuterium (D), and the n's are the respective densities; f is the ionisation probability. If the respective flow velocities of the different particle species just differ by the mass difference, then the nitrogen concentration in the divertor plasma would be larger than in the neutral gas as the ionisation probability of nitrogen is larger (factor 2.5). For other situations, particularly with different parallel transport mechanisms, the result is not as clear and a more detailed inspection is needed.

5. Summary and conclusions

5.1. Deuterium retention

Ohmic discharges with density ramps to reach plasma detachment from horizontal target plates show improved neutral particle retention during the transition from lower to higher recycling regimes but deteriorating retention when detachment sets in. The change of transparency of the divertor plasma for neutrals appears to play an important role. Deuterium retention is unlikely to be only controlled by the presence of structural leaks in the JET divertor module. The magnitude of neutral retention can be, but needs not be affected by the magnetic configuration. High magnetic flux expansion in JET did not measurably improve the retention but bears the risk of bringing recycling closer to the main plasma by SOL plasma scraping at the vertical baffle plates, resulting in reduced retention. The precise positioning of the divertor plasma within the divertor module is important. The separatrix in the corner position between the horizontal and the vertical target plate gives the highest neutral deuterium retention of all configurations.

5.2. Nitrogen retention

First results of detached steady state ELMy H-mode with seeded nitrogen as a radiating impurity shows rather high nitrogen concentration in the divertor gas, with enrichment factors of about 30 or more. However, Z_{eff} is rather high too, reaching values larger than about 2.5.

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