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# Long discharges in steady state with D<sub>2</sub> and N<sub>2</sub> on the actively cooled tungsten upper divertor in WEST

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## Abstract

Nitrogen (N<sub>2</sub>) will be used in ITER to enhance the radiative fraction to ~90% to cool the edge plasma and prevent damages on plasma facing components. However, the reactivity of N<sub>2</sub> with hydrogen isotopes can lead to the formation of tritiated ammonia (NT<sub>3</sub>). This should be considered for the in-vessel tritium inventory, the re-generation of the cryo pumps and the processes in the de-tritiation plant in ITER.

In WEST, series of long L-mode discharges (~50s), with a constant N<sub>2</sub> seeding from the outer strike point region have been performed on the upper actively cooled divertor. In the absence of active pumping, the N<sub>2</sub> balance shows a steady state retention during the plasma whilst partially (~35%) released in between discharges. Although a significant amount of N<sub>2</sub> (18.65 Pam<sup>3</sup>) has been injected, the wall still exhibits N<sub>2</sub> pumping capabilities. In these conditions, as far as this N<sub>2</sub> reservoir is not saturated, there is not enough N available for reaching the detectable threshold of ND<sub>3</sub> formation. In these WEST experiments no ammonia is detected during the pulse or after the pulse in the outgassing phase. These results are consistent and complementary to the N<sub>2</sub> seeded experiments performed in JET with its ITER like wall and in ASDEX-Upgrade.

**Keywords:** WEST, long pulses, steady state, plasma surface interaction, nitrogen seeding, ammonia.

## I - Introduction

Heat load control on plasma facing components (PFC) is a critical issue in magnetically confined fusion devices. Plans for the operation of ITER and DEMO will rely on the injection of low-Z impurities for potentially improving the plasma confinement but particularly for reducing the heat loads on the PFCs through enhanced radiation in the edge plasma. Indeed, the current design of the technologically achievable level for the materials that will be used in ITER is in the range of  $10 \text{ MWm}^{-2}$  in steady state and transiently  $20 \text{ MWm}^{-2}$  [1, 2]. Without this enhanced edge radiation, the heat flux at the divertor strike point is expected to reach ranges  $>50 \text{ MWm}^{-2}$  which is by far above the acceptable power threshold of the PFCs. With carbon-based PFCs, high carbon concentration in the edge plasma was achieved through erosion and transport in the edge plasma leading to high radiation in the vicinity of the divertor targets. With fully metallic PFCs, such as in the full tungsten ASDEX-Upgrade (AUG), the JET with its ITER-like wall (JET-ILW) and to a further extend ITER and DEMO, the intrinsic concentration of low-Z impurities is significantly lower. Therefore, low-Z impurities have to be introduced into the edge plasma as seeded gases [3] for dissipating a sufficiently high fraction of the energy entering the scrape-off layer (SOL) in order to reduce and to control the divertor heat loads. So far, most of the investigations on high radiating plasma scenario in metallic fusion devices have been focussed on Argon, Neon and Nitrogen whilst few were performed with Krypton and Xenon [3]. In this context, compared with the carbon environment, the nitrogen seeding has allowed for similar plasma performances [4] due to the very close radiation functions of N and C.

However, the potential reactivity of  $\text{N}_2$  with hydrogen isotopes can lead to tritiated ammonia ( $\text{NT}_3$ ) as well as  $\text{ND}_x$  and  $\text{NT}_y$  formation, which should be considered for the re-generation of cryo pumps and processes in de-tritiation plants. In ITER, the tritium plant will have to decompose ammonia to recover the tritium since, in terms of safety, a maximum of 180g is allowed in the cryopumps. In addition, the potential formation of nitrogen oxides should also be avoided in the high temperature process required for  $\text{NT}_3$  recovery [1].

Also, the activation of these low Z seeding gases (Argon, Krypton, Neon, Nitrogen and Xenon) in nuclear environments is another issue often neglected. Although not discussed in this work, the consequences of the potential activation of these gases and their respective progenies through the neutron flux generated during DT operations are reported in [5] for DEMO scenario.

The quantification of the ammonia formation through surface reactions between nitrogen and hydrogenic species on PFCs has still to be completed. At this stage, it is not yet possible to predict

the ammonia formation rates expected in the different ITER plasma scenario [2]. However, using N<sub>2</sub> in the ITER facility as radiator in the edge plasma and particularly in the divertor is still nevertheless considered as a viable seeding candidate for the size and conditions of present day PFCs and particularly the divertor.

The work reported in this paper concentrates on the N<sub>2</sub> injection and the potential formation of ammonia (ND<sub>3</sub>). The objective of the reported experiments is to study the pumping behaviour of N<sub>2</sub> with metallic PFCs and ammonia formation due to the N<sub>2</sub> injection over long discharges.

The tokamak Tore Supra, initially designed for long pulse operation, has recently been modified to WEST [6, 7] with a change from a limited to a diverted magnetic configuration and from carbon to tungsten PFC. The aim of this project is to test the ITER divertor technology through long discharges for material behaviour studies, to assess the consequences of high fluences on tungsten PFCs and also the corresponding effects on plasma performances. In this context, series of long pulses in steady state with N<sub>2</sub> seeding have been carried out in WEST for assessing the N<sub>2</sub> particle balance and the potential ammonia formation in a full actively cooled tungsten device. The objectives were to improve the understanding of physics of the ammonia production, its decomposition and transport in a magnetically confined plasma devices. In this study, the overall N<sub>2</sub> particle balance is evaluated through the long discharge configuration and steady state capabilities of WEST on the actively cooled upper divertor. These experiments are therefore complementary to those already carried out in both JET-ILW and AUG [8, 9] with inertial PFCs leading to high surface temperature and limited plasma duration in the range of 6-7s.

For the reported configuration, WEST is in its “*phase 1*” [6] equipped with a mix of ITER-like actively cooled PFUs (bulk W designed for heat flux up to 20MWm<sup>-2</sup>) and non-actively cooled W-coated graphite components (W-coating ~20µm thick) in the lower divertor. The upper divertor is fully equipped with actively cooled copper based PFC, coated with ~20µm of tungsten allowing long discharges in steady state conditions. In upper single null configuration (USN) heat flux up to 8MWm<sup>-2</sup> and/or a total heat removal capability in steady state of 5MW can be achieved. Although no active pumping has been installed in the upper divertor, long discharges in USN configuration are now routinely operated [10]. In this study, five repetitive long deuterium (D<sub>2</sub>) discharges in the range of 50s in steady state have been performed in the USN configuration with constant N<sub>2</sub> injection up to 35s from the outer strike point region (OSP) for assessing the N<sub>2</sub> particle balance and the resulting potential ND<sub>3</sub> formation.

In the first section, the experimental context and the main plasma parameters are reported based on the main diagnostic measurements through the Langmuir probes, the bolometry, the VIS, UV spectroscopy and the mass spectroscopy. In the second section the particle balance for both  $D_2$  and  $N_2$  is described in complement to the monitoring of  $ND_3$  during the plasma and the recovery phases. The last section is dedicated to the discussion and the comparison of these results with those obtained in JET-ILW [8] and AUG [9].

## II - Plasma experiments

The reported series of experiments has been performed after the 40 pulses that have followed a boronisation. These 40 plasmas cumulate a duration of 452s with 30 pulses (total of 166s) in Lower Single Null (LSN) configuration and 10 long discharges (total of 286s) in USN. Among these 40 discharges, 25 have been run with a lower hybrid (LH) auxiliary heating,  $P_{LH}$ , ranging from 1.0 to 4.4MW. In this context, the potential effects of the boronisation performed with 10% diborane ( $B_2D_6$ ) and 90% Helium using glow discharge were considered as negligible on the plasma both in terms of recycling and impurity content. This is also supported by the 10 repetitive discharges performed in USN (without  $N_2$  injection) prior to these experiments and including a discharge (# 55786) in USN with 3.0MW of lower hybrid heating ( $P_{LH}$ ) for 55s. All these repetitive discharges exhibit the same main parameters (density, radiated power...) in the first seconds (~0- 3s) of the plasma as well as during the different heating phases whilst the level of oxygen has remained in the range observed prior to the boronisation.

For these experiments, the main parameters were a plasma current,  $I_p$ , of 400kA, a toroidal field,  $B_T$ , of 3.7T, a  $P_{LH}$  of 3.0 MW, a line integrated plasma density,  $n_l$ , of  $3.3 \times 10^{19} m^{-2}$  in L-mode and in USN configuration. In this plasma configuration, there is no active pumping in the sub-divertor region for controlling the plasma density or the  $N_2$  plasma content. The only pumping system for these experiments is the “maintenance” system (Turbo pumps) ensuring the basic pressure in the vacuum vessel and the five turbo-pumps located on the lower sub-divertor. However, as it will be shown, these pumping systems are not efficient at all for particle exhaust during USN plasma operations. This means that all the gas ( $D_2$  and  $N_2$ ) injected remains in the plasma volume and/or in the wall (through implantation and co-deposition). On the one hand, the absence of active pumping appears as an operating challenge for both plasma density and radiated fraction control with a constant impurity injection over durations in the range of 40s. On the other hand, during the steady state phase, for a constant plasma density, the gas balance directly exhibits the “net” wall pumping rate for both  $D_2$  and  $N_2$ .

The reported experiments focus on five long discharges (~50s range each), the first one (# 55787) being used as a reference without  $N_2$  injection. For the 4 following pulses, a constant  $N_2$  seeding was applied from the OSP region. **Figure 1** shows a poloidal cross section of the USN plasma configuration (# 55789 @15.42s) with the location of  $N_2$  injection feedforwarded at a constant rate in the OSP region. The  $D_2$  is injected through the mid-plane with a feedback control for achieving a constant density over the entire plasma duration. In **table I** a summary of the  $D_2$  and  $N_2$  injection rates and quantities is presented. For these five consecutive and repetitive discharges, the same  $D_2$

injection rate in the range of  $\sim 0.15\text{-}0.2 \text{ Pam}^3\text{s}^{-1}$  ( $\sim 10^{20}\text{Ds}^{-1}$ ) has always been required for maintaining the plasma density constant over the 50s of discharge. **Figure 2** shows the main plasma parameters ( $I_p$ ,  $n_i$ ,  $P_{LH}$ ,  $P_{rad}$ ,  $D_2$  and  $N_2$  injection rates) for the pulse # 55789 representative of this series with  $N_2$  seeding. After  $\sim 25\text{-}30\text{s}$ , all the plasma parameters are in steady state and, remarkably, this is the case for all these five reported discharges.

For the 4 seeded pulses, the total amount of  $N_2$  injected through the OSP region is  $18.65 \text{ Pam}^3$ . This is a significant amount of  $N_2$  that can be compared to experiments reported in [10] where a total of  $5.4 \text{ Pam}^3$  were injected over 6 pulses with injection for a maximum of 6s @  $0.15 \text{ Pam}^3\text{s}^{-1}$ . The higher rate and amount of  $N_2$  has been obtained for the discharge # 55792, in which a total of  $9.49 \text{ Pam}^3$  of  $D_2$  ( $4.58 \times 10^{21} \text{ D}$  &  $4.58 \times 10^{21} \text{ e}^-$ ) and  $6.32 \text{ Pam}^3$  of  $N_2$  have been injected ( $3.1 \times 10^{21} \text{ N}$  &  $21.3 \times 10^{21} \text{ e}^-$ ).

Except for the discharge # 55790,  $N_2$  injection is also performed in the early phase of the plasma from 0 to 3s. This injection allows for an increase of the edge radiation during the limiter phase and the early X point phase (X point is formed at 1.0s) when  $I_p$  has reached 300kA. This procedure allows for an enhanced radiation at the edge for limiting the W impurity generation whilst peaking the plasma current profile, temperature and density. In this phase (0 to 3.0s), the plasma is generally detached and it reattaches during the  $I_p$  ramp up from 300 to 400kA. However, the amount of  $N_2$  injected during this early plasma phase is negligible compared to the injection during the steady state phase (see **table I**). In addition, this early and minor  $N_2$  injection has no effect or contribution at all on the plateau phase of the discharge and on the next pulse as it will be shown in the discussion.

**Figure 3** shows the comparison between two consecutive discharges, the first one (# 55787) without  $N_2$  and the second (# 55789) with a constant  $N_2$  injection through the OSP from 10 to 40s @  $0.1 \text{ Pam}^3\text{s}^{-1}$ . No difference can be distinguished on the main plasma parameters between these two discharges. The plasma temperature,  $T_e$ , at the OSP region is measured through the Langmuir probes located in the upper divertor.  $T_e$  is in a range of 5-10eV in the ohmic phase prior the LH power whilst it increases around  $\sim 15\text{-}20 \text{ eV}$  during the heating phase. Over the entire heating phase when  $N_2$  is injected, no effect is observed on  $T_e$  which remains in this range of 15-20eV. Consistently with these results, the maximum surface temperature at the OSP region is around  $300^\circ\text{C}$ , stable since actively cooled, but without any drop or even a variation of the surface temperature during the  $N_2$  injection. The only effect clearly observed appears on the saturation current measured by the Langmuir probes which increases by 25% from 4 to  $5 \times 10^{-3} \text{ A}$ . Also, as the  $N_2$  injection is turned on, the electron flux increases up to a steady state whilst it recovers its initial value (prior to the injection) as the seeding is stopped. Several plunges performed with the reciprocating Langmuir probe in similar plasma pulses

(see [10]) allow for both  $T_e$  and  $n_e$  evaluation up to a normalised radius of  $\rho=r/a\sim 1.05$  showing about  $T_e\sim 75\text{eV}$  and  $n_e\sim 1.6\times 10^{19}\text{m}^{-3}$  at the separatrix. Except a small increase of the density in the SOL during the injection, no effect is observed.

The spectroscopic analysis in the VIS range exhibits an increase of the NII signal (@399.6nm), as more N is injected from discharge to discharge. This effect is more pronounced in the surrounding of the OSP (where  $\text{N}_2$  is injected) but this remains a very small effect which stays constant over the injection showing no accumulation in the vicinity of the edge region and particularly close to the location of the main recycling flux. This is confirmed by the bolometry measurements showing that the overall profile of the radiated power is nearly not modified. Indeed, only the edge tracks of the bolometry exhibit a very minor increase of the signal in the vicinity of the OSP over the  $\text{N}_2$  injection duration. The two tracks probing the edge plasma in the OSP region (# 14 and # 15 – see figure 1) show an increase by  $\sim 8\%$  and recover their initial values as the injection is stopped as illustrated on **figure 4**. This effect is not observed for the lower tracks # 2 and # 3 viewing the lower part of the plasma and SOL. This strongly suggests that the extra radiation (although modest) due to  $\text{N}_2$  injection remains only as a “local” effect in the recycling area.

Going deeper in the plasma, the  $\text{N}_2$  injection can be weakly observed in the UV range @247.6 Å for the NV signal and @ 24.8 Å for the NVII signal when averaged over 5s (from 25-30s). This is shown on **figure 5** where the NVII signal @ 24.8 Å is plotted as a function of time for the discharge 55792 where the strongest  $\text{N}_2$  injection has been performed (35s @ $\sim 0.21\text{ Pam}^3\text{s}^{-1}$ ). As for the bolometry, a steady state phase is observed for  $t>25\text{-}30\text{s}$  whilst the signal drops back to its initial value prior to the seeding phase as the injection is stopped. On **figure 5**, the NVII signal @ 24.8 Å is plotted as a function of time for the discharge # 55790 with no early  $\text{N}_2$  injection and showing that the early NVII signal peak is not observed confirming the absence of  $\text{N}_2$  legacy from previous  $\text{N}_2$  seeding for 30s at a rate of  $0.1\text{ Pam}^3\text{s}^{-1}$ . In the absence of active pumping during the plasma operation one could have expected a cumulative effect of the  $\text{N}_2$  during the discharge (seeding duration up to 35s) and also from pulse to pulse. However, no such effect at all has been observed. From these experiments, evidences are highlighted that the  $\text{N}_2$  injected goes only very weakly in the bulk plasma whilst totally dominated by the wall pumping.

Finally, in terms of spectroscopy, no effect can be observed on the other main plasma impurities such as W, O, C or B. These measurements exhibit a very consistent overview of the very weak effect of the  $\text{N}_2$  injection on the radiation pattern (bulk and edge), and confirmed by the Langmuir probes and the IR measurements.



The N<sub>2</sub> balance has been monitored by the RGA located in the main pumping duct at the outer mid-plane (see **figure 1**) of the vacuum vessel. During the plasma operation, the edge neutral pressure in the mid-plane is very low, always below the 1.0x10<sup>-3</sup> Pa range for all the discharges and always with D<sub>2</sub> as the dominant species. For all these discharges, the same behaviour of N<sub>2</sub> is observed more or less independently of the amount injected. **Figure 6** shows the time evolution of the mass 28 (N<sub>2</sub>) recorded by the RGA during the plasma and the recovery phases for the five discharges of the series; # 55787 being run without N<sub>2</sub> injection during the heating phase. This clearly shows that compared to the amount injected a totally negligible amount of N<sub>2</sub> is pumped during the pulse through the mid-plane; this point is discussed later in the paper. After the pulse, the N<sub>2</sub> recovery increases with respect to the amount injected. However, from pulse to pulse, no real legacy effect can be observed. Indeed, the increase in the mass 28 can be attributed to the stronger seeding, but no effect is observed during the breakdown and the first seconds (0-3 s) of plasma as shown on **figure 6**. Finally, for the last pulse (# 55794) of this series, strong MHD activity occurred during the heating phase leading to a disruption during the heating phase. This can explain the higher recovery due to different/enhanced plasma wall interaction with the potential N<sub>2</sub> reservoir.

From the RGA data, the mass spectra of ammonia overlaps with methane and water, which are part of the neutral gas composition in the mid-plane during both the pulse and post pulse phases. The model described in detail in [11], allows for the proportion of each of the three gas to be evaluated. This model is the same as the one used for both the JET-ILW [8] and AUG [9] N<sub>2</sub> injection and ammonia experiments. For the WEST experiments, the signals of water, methane and ammonia are shown on **figure 7** for the discharge # 55792. These results clearly indicate that the ND<sub>3</sub> stays below the detection limit both during the plasma operation and the recovery phase. This is also the case even for the discharge # 55792 which contained the most nitrogen and for the last discharge (# 55794) showing a higher N<sub>2</sub> recovery after the pulse due to the disruption.

During the four discharges cumulating more than 3 minutes of plasma, N<sub>2</sub> has been seeded through a toroidal ring located below the upper divertor in the vicinity of the outer strike point (OSP). The nitrogen seeding rate has been ranging from 0.1 to 0.22 Pam<sup>3</sup>s<sup>-1</sup> for a total duration of 125s for investigating both the potential legacy of N<sub>2</sub> injection on plasma performances and the formation of ND<sub>3</sub> in steady state conditions. Thanks to the actively cooled PFCs the surface temperature has reached a maximum of 300°C in steady state. For all these discharges, the main radiative impurities have been identified as W, O, Cu (mainly during the LH power phase) including some traces of C. The contribution of N in the overall radiation has always been found to be negligible although N has been observed through both VIS and UV spectroscopy and only during the N<sub>2</sub> seeding phases.

### III – Particle balance

The particle balance performed for the overall vessel at the mid-plane (and also the RGA location, see **figure 1**) for both D<sub>2</sub> and N<sub>2</sub> species can be expressed as:

$$\int_0^t \Gamma_{inj} dt = N_{Plasma} + \int_0^t P S dt + N_{Wall} \quad (1)$$

where  $\Gamma_{inj}$  is the gas injection rate,  $N_{Plasma}$  is the plasma fuel content,  $P$  the neutral pressure close to the pumps at the mid-plane,  $S$  the equivalent pumping speed, resulting from the lower divertor pumps and the maintenance pumping system and  $N_{Wall}$  is the amount of particles trapped or released by the wall since the start of the plasma at  $t = 0$ .

This balance is verified at any time during the plasma discharges for each species (D<sub>2</sub> and N<sub>2</sub>) and also after the pulse during the outgasing phase. The total neutral pressure in the vessel,  $P_{tot}$ , close to the RGA is measured through a “baratron” type pressure gauge. Based on the RGA measurements, the composition of the gas released after the pulse is totally dominated by D<sub>2</sub> and N<sub>2</sub> whilst the “traces” of H<sub>2</sub> and H<sub>2</sub>O are negligible in the gas balance.

For these experiments in USN, during the plasma, the neutral pressure in the pumping systems (lower divertor and maintenance) is always lower than a 0.5-1.0x10<sup>-3</sup> Pa range. With a total pumping speed of 9.8m<sup>3</sup>s<sup>-1</sup> for the D<sub>2</sub>, this leads to a maximum pumping rate of 0.01 Pam<sup>3</sup>s<sup>-1</sup> by far less and negligible compared to the D<sub>2</sub> injection rate in the range ~0.2 Pam<sup>3</sup>s<sup>-1</sup>. The same conclusion results for N<sub>2</sub> since, although very low, no significant increase is measured in the mid-plane during plasma. With such a negligible particle exhaust by the pumps, this confirms that for all these discharges the wall represents the main pump during plasma. Throughout this situation without active pumping in USN, since the plasma density is constant, this leads to a constant retention process in a range of ~0.2 Pam<sup>3</sup>s<sup>-1</sup> independently of the cumulated amount of D<sub>2</sub> and N<sub>2</sub> injected in the previous discharges. In these conditions, the particle balance is dominated by the recovery phase following the end of the plasma and simply described through equation 1 where  $N_{Plasma}=0$ .

The gas balance is focussed on the comparison of the reference pulse w/o N<sub>2</sub> injection (# 55787) and the pulse (# 55792) with the strongest N<sub>2</sub> injection. For the pulse # 55787 (duration of 53s) 11.6Pam<sup>3</sup> of D<sub>2</sub> has been injected and for the pulse # 55792 (duration of 49.3s), 9.49 Pam<sup>3</sup> of D<sub>2</sub> and 6.32Pam<sup>3</sup> of N<sub>2</sub> have been injected. Except for the N<sub>2</sub> injected, these two discharges are very close

both in terms of plasma parameters ( $I_p$ ,  $B_T$ ,  $P_{LH}$ ,  $n_l$ , and plasma shape in USN), duration and  $D_2$  injection rates.

For the pulse w/o  $N_2$  injection (# 55787), the time evolution of the total neutral pressure in the vessel after the discharge exhibits a usual  $\sim t^{-0.7}$  dependence and the extrapolation shows that the initial pressure in the vessel is recovered after about 30min. This is illustrated on **figure 8** where the time traces of the  $D_2$  pressure and the fit with a function  $\alpha t^{-0.7}$  are plotted for discharge # 55787. The particle balance shows that  $9.5 \text{ Pam}^3$  of  $D_2$  have been pumped that have to be compared to the  $11.6 \text{ Pam}^3$  injected for this discharge.

The particle balance for the discharge # 55792 with both  $D_2$  and  $N_2$  injection exhibits a very similar behaviour for the  $D_2$ . Indeed, a total amount of  $9.5 \text{ Pam}^3$  has been injected and according to the fit (also using a  $t^{-0.7}$  law), the recovery of the initial  $D_2$  vessel pressure occurs at  $\sim 25$ min (See **figure 8**). Based on this fit, the  $D_2$  balance shows that  $9.0 \text{ Pam}^3$  (94%) has been exhausted which is the highest recovery of the series. For all the other discharges, an average  $D_2$  recovery in a range of  $\sim 80\%$  (see **table I**) is observed after more than 30min, which is very consistent compared to what can be expected in a metallic device [8, 9].

The  $N_2$  pressure and the associated balance for the pulse # 55792 show that the total  $N_2$  recovered after 25 min is  $2.0 \text{ Pam}^3$ , corresponding to 32% of the total  $N_2$  injected. From these experiments, a different time dependence for  $D_2$  and  $N_2$  pressure in the recovery phase can be observed. Indeed, as shown on the insert on **figure 8**, the maximum pressure of  $D_2$  is reached @53 s (end of pulse @49.3s) whilst the maximum  $N_2$  pressure is observed later @58s. Also, the fit for the partial pressure of  $N_2$  has to be adjusted by a  $t^{-1.6}$  law suggesting a different outgassing process than the  $D_2$ . In these conditions, after about 700s after the end of the pulse, the  $N_2$  pressure has recovered values that are very close to values prior to the pulse. In these experiments, the temperature of the actively cooled PFCs is back to the initial temperature ( $70^\circ\text{C}$  in the case of WEST) in less than 30s after the pulse. For the discharges # 55790 and # 55792, applying the same seeding rate, a remarkable reproducibility of both the  $D_2$  and  $N_2$  balance is observed. For the last pulse of the series (# 55794), the larger  $N_2$  recovery is much more due the disruption during the heating phase whilst the plasma interacts strongly with the upper divertor. The amount of  $N_2$  recovered after 25 min is in the range of  $3.0 \text{ Pam}^3$ , corresponding to 70% of the amount injected ( $4.39 \text{ Pam}^3$ ). For the seeded pulses, the amount of  $N_2$  recovered 30 minutes after the end of the pulse is in a range of 35% whilst higher values can be reached after a disruption (see **table I**). This also suggests that most of the  $N_2$  is retained in surfaces “viewing” the plasma.

Although the neutral pressures (total and partial) at the end of all these discharges are rather high, meaning that the signal to noise ratio exhibits favourable conditions, no  $\text{ND}_3$  is detected at all in the RGA during the discharge or at the end of the discharge when the plasma recombines and during the 30 min of outgassing between pulses.

#### **IV Discussion**

Except for one pulse (#55790),  $\text{N}_2$  has been injected at the beginning of the plasma (0-3s) during the limiter phase (0-1s) and the early X-point phase (1-3s) through the mid-plane and the effect of this injection has not at all the same effect on the plasma. In the one hand, this amount, being in the range of 0.15-0.2  $\text{Pam}^3$ , is totally negligible compared to the 2.46 to 6.32  $\text{Pam}^3$  injected during the X-point and heating phases. On the other hand, this early injection is very well detected by the RGA as neutrals at the edge plasma and in the confined plasma as confirmed through both the NV and NVII signals which exhibit a “peak” at the beginning of the plasma. If no  $\text{N}_2$  is injected during this early plasma phase, no  $\text{N}_2$  is detected at all even if  $\text{N}_2$  has been seeded during the heating phase in the previous pulse. This is illustrated through the pulse # 55790 on **figure 6** and this behaviour demonstrates that there is no legacy of the  $\text{N}_2$  injected during the previous plasmas.

These results also support the fact that the  $\text{N}_2$  reservoir is primarily located close to the OSP region where the  $\text{N}_2$  is injected. Indeed, when compared to long discharges performed in the same conditions with  $\text{N}_2$  injected through the mid-plane,  $\text{N}_2$  was detected by the RGA during the plasma meaning that all this  $\text{N}_2$  is not fully ionised and a part can be directly pumped by the main pumping system as suggested in [10]. As a consequence, since no legacy is observed over this series of experiments, these measurements by the RGA support the fact that nearly no (totally negligible)  $\text{N}_2$  is exhausted during the discharge and that a significant part (~35%) of the retained nitrogen over the discharge is released after the discharge.

For the four seeded discharges, the overall N balance exhibits a reservoir in the range of  $\sim 6 \times 10^{21} \text{N}$  (~65% of the total  $\text{N}_2$  injected). If we assume that the N sticks to the W wall, with a density in the range of  $1 \times 10^{19} \text{Nm}^{-2}$ , this supposes a flat W surface of  $600 \text{m}^2$  which is not consistent with the  $\sim 100 \text{m}^2$  of the surface in view of the plasma ( $\sim 20 \text{m}^2$  for both the lower and upper W divertors and  $80 \text{m}^2$  for the stainless steel first wall). Considering the ion implantation and the neutral penetration in the bulk W, the retention can reach  $2 \times 10^{20} \text{Nm}^{-2}$  [12] with ion energies in the range of 250-500eV. Such a retention could be obtained with surfaces of  $\sim 30 \text{m}^2$ , which appears to be close to the exposed W surface of the upper divertor ( $10 \text{m}^2$ ). However, the upper divertor is made of copper with a W coating

of 15-20 $\mu\text{m}$ . The porosity of such a coating is larger than the W bulk contributing to the absence of saturation of the N reservoir.

Also, since, the effects of the boronisation can be observed (using O as the reference) over a maximum of  $\sim 15$ -20 pulses, this N<sub>2</sub> reservoir cannot be attributed to the boronisation performed more than 40 pulses before these experiments whilst the O signal for all these experiments is in the same range as for the few discharges performed just prior to these N<sub>2</sub> experiments.

These results have to be compared to those obtained in JET-ILW [8] and AUG [9] equipped with non-actively cooled divertor W coating targets. In the seeded L-mode experiments ( $I_p/B_T=2.0\text{MA}/2.2\text{T}$ ) reported in JET-ILW [8], the N<sub>2</sub> was injected into the divertor scrape-off layer through the toroidally symmetric gas injection ring (Gas Introduction Module: GIM 9) in the vicinity of the horizontal W target plate (so called “tile 6”) where the OSP was positioned. Injection rates between  $1.4$  and  $5.4 \times 10^{21} \text{ e}^- \text{ s}^{-1}$  (respectively  $0.2$  and  $0.77 \times 10^{21} \text{ N s}^{-1}$ ) have been applied for 4-5s for 10 discharges. A total amount of  $3.62 \times 10^{22} \text{ N}$  has been injected over 10 discharges. This correspond to a rate 6-7 times higher than in WEST ( $9.0 \times 10^{21} \text{ N}$ ) but for a shorter duration (4-5s compared to 40s) whilst the injection location is very close to the gap entrance where the cryopump is installed. In these JET-ILW experiments, the gas balance measurements indicate a N<sub>2</sub> retention in the range of 50% (same range observed in WEST) and also a significant increase in D<sub>2</sub> retention compared to reference experiments. Whilst no effect of N<sub>2</sub> injection has been noticed at all on the D<sub>2</sub> balance in WEST, according to the author, this “extra” D<sub>2</sub> retention in JET-ILW can be attributed to the N<sub>2</sub> seeding through ammonia formation corresponding to roughly 15% of the injected N atoms converted to ND<sub>3</sub>. This is a huge percentage which is not supported from the experiments reported from AUG and discussed below. In addition, in these L-mode experiments, no clear evidence of ND<sub>3</sub> formation is detected in the RGA located in the divertor region although ND line is observed (@336.0nm) during plasma operations. The absence of clear measurements is attributed to the long distance from the ammonia formation to the RGA location in accordance to a production rate below the sensitivity of the RGA system between pulses.

In AUG, the N<sub>2</sub> injection experiments have been performed in a H-mode discharge with both ECRH and NBI heating with an averaged plasma density of  $7 \times 10^{19} \text{ m}^{-3}$ , a stable flat-top phase before the onset of nitrogen seeding [9]. The N<sub>2</sub> was injected into the private flux region, at a constant seeding rate of  $1.7 \times 10^{21} \text{ N s}^{-1}$  adjusted for keeping the outer divertor in an attached state. A total amount of  $4.05 \times 10^{22} \text{ N}$  has been injected over 6 discharges. In AUG, three RGAs were used, for potential ND<sub>3</sub> detection, located in the inner divertor, in the outer divertor and in the mid-plane. In these experiments evidence of ammonia formation are reported during the plasma operation particularly in

the inner divertor as it was an order of magnitude higher than the impurity partial pressures in a non-seeded discharge. The amount corresponds to a 2% concentration in the neutral gas. This is very low compared to the 15% suggested in JET-ILW [8] which in the reported context (ammonia amount evaluated from the  $N_2$  and  $D_2$  retention) seems strongly overestimated. However, during the plasma, a huge difference on the gas composition appears between the inner and the outer divertor respectively dominated by ammonia and water. Although not discussed, this could be linked to the detached conditions of the inner leg leading to a lower ionisation rate of the potential  $ND_3$  formed in the vicinity of the inner strike point (ISP). The absolute values of the ammonia pressure is also 50 times higher in the inner sub-divertor region compared to the outer, whilst the  $N_2$  pressure in the midplane remains very low and no sign of ammonia is detected during the plasma. In AUG, the authors report that while ammonia can be formed in surface reactions both on plasma-facing and plasma-shaded surfaces, it is only the ammonia formed on plasma-shaded surfaces that can make a significant contribution to the net ammonia production. The authors suggest that the ammonia formed in the divertor could not migrate to the midplane in the discharge phase as it is promptly dissociated to N and D atoms in the plasma and supporting that no ammonia can be detected in the midplane before the end of the discharge. This can appear to be somewhat contradictory with the results observed in WEST where the upper divertor is open and where the absence of compression generated by a close divertor (as on both AUG and JET-ILW) appears as favourable conditions for both the  $N_2$  and the  $ND_3$  formed to migrate up to the mid-plane. However, this means that a significant amount of  $ND_3$  has to be formed prior to any migration compared to reionisation, which is likely not the case in WEST. Although the amount of N injected in WEST ( $9.0 \times 10^{21} N$ ) can appear low compared to JET-ILW and AUG with respectively  $3.62 \times 10^{22}$  and  $4.05 \times 10^{22} N$  injected, it is worth reminding that the absence of  $N_2$  pumping in WEST allows for all the  $N_2$  injected to be dissociated (and therefore potentially forming  $ND_3$ ). In both JET-ILW and AUG a non-negligible part (always very difficult to assess) of the injected  $N_2$  is directly pumped by the cryo-pumping systems making the direct comparison of the absolute amount of N injected not as the primary criteria.

For all these three experiments (JET-ILW, AUG and WEST), the presence of ammonia formation resulting from  $N_2$  injection is deduced through a model. Indeed, the mass spectra of ammonia overlaps with methane and water, which are part of the neutral gas composition in the sub-divertor region and the mid-plane during both the pulse and post pulse phases. The same model, described in detail in [11], is used for the three reported experiments and allows for the proportion of each of the three gas to be evaluated. From the three experiments, the strong increase of ammonia deduced in AUG appears as very convincing in the  $ND_3$  formation in the sub-divertor area particularly when compared to the non-seeded case. However, it could be worth repeating these experiments with  $N^{15}$  isotope allowing

for a single mass monitoring preventing any discussion and doubt on the fits that have to be performed when using  $N^{14}$  for sorting out the overlap of ammonia, water and methane in the analysis of the RGA data.

Compared to the JET-ILW and AUG experiments, the results observed on WEST can lead to the following interpretation. Since there is no active pumping and since no increase of the radiation is observed, the  $N_2$  balance in the WEST experiments clearly shows that there is a reservoir of  $N_2$  which is filled up during the plasma, but without reaching the saturation. This reservoir totally dominates the  $N_2$  balance and as far as the saturation is not reached this could be the reason why no ammonia at all is detected throughout all these experiments (plasma and outgassing phase). In other words, as far as this  $N_2$  reservoir is not saturated, there is no or not enough N available for a significant  $ND_3$  formation. This is also complementary and consistent with the results obtained both in JET-ILW and AUG suggesting that the ammonia formation occurs only in the vicinity of the sub-divertor region (recycling regions). This is also very likely the dominant location of the  $N_2$  reservoir since except in the divertor, no  $N_2$  is detected in the mid-plane during plasma operations even in AUG. In JET-ILW the presence of ammonia was very weak and could be the signature of the non-saturation of the  $N_2$  reservoir. In WEST, according to the NVII behaviour (**figure 5**), it is very clear that this reservoir is not saturated at all explaining a weak  $ND_3$  production that cannot be detected. In AUG, in spite of the strong ammonia production in the inner divertor associated with a high  $N_2$  injection compared to JET-ILW and WEST, it is worth noting that few second after the pulse, the signature of ammonia disappears very quickly in the divertor (inner and outer) whilst it always remains very low in the mid-plane. The results obtained in the three devices are consistent with the potential saturation of the  $N_2$  reservoir prior to potential significant  $ND_3$  formation above the detection threshold. In WEST, although the particle flux is significantly lower than it will be in ITER, the edge  $T_e$  in the divertor region was in the same range as predicted for ITER. These plasma conditions, in the vicinity of the strike points as well as the constant surface temperature over these long durations due to actively cooled PFCs are relevant to what is expected in ITER.

Further experiments, with repetitive long discharges in steady state, with a higher radiating fraction (likely semi-detached plasma) with constant  $N_2$  seeding ( $N^{15}$  encouraged) would allow for clarifying the  $N_2$  reservoir, its potential saturation leading to a threshold enhancing the corresponding rate of  $ND_3$  formation and release.

#### IV - Conclusion

Series of long and steady state discharges in USN have been performed with a constant N<sub>2</sub> seeding from the OSP region cumulating 237 s of plasma (~4min). A total of 18.65 Pam<sup>3</sup> of N<sub>2</sub> has been injected in 4 consecutive discharges through the OSP during up to 35s and with injection rate of 0.21 Pam<sup>3</sup>s<sup>-1</sup>. For all these experiments with N<sub>2</sub> seeding, a very weak effect on the radiated power (edge and bulk) has been observed. In the absence of active pumping, at this injection rate, steady state conditions are reached, showing that there is a constant retention of the N<sub>2</sub> whilst no saturation is observed for duration in the range of 35s. The D<sub>2</sub> recovery for these long discharges is in a range of 80-85% which is consistent with what can be expected for metallic devices. Also, the D<sub>2</sub> retention and recovery does not appear to be influenced by the N<sub>2</sub> injection. The N<sub>2</sub> recovery during the 25-30 min following the pulse is in the range of 35% whilst it can reach up to 70% during a disruption. In the absence of active pumping, a saturation of the N<sub>2</sub> wall pumping over the seeded duration could have been expected. This has not been the case at all and since no legacy from the N<sub>2</sub> injection has been observed on the following pulse, this shows that the N<sub>2</sub> reservoir is not saturated.

Considering the N<sub>2</sub> balance over such long time scales and in the absence of active pumping in USN configuration, these experiments suggest that the majority of the injected N<sub>2</sub> is retained in the the upper divertor made of copper with a W coating of 15-20µm. The porosity of this coating is larger than the W bulk enhancing the volume of this N reservoir. As a consequence, since the saturation of this reservoir is not reached, this results in a very weak ND<sub>3</sub> production. Prior to this saturation, no or not enough N is available for ND<sub>3</sub> formation, explaining that no ND<sub>3</sub> at all is detected in the WEST experiments. Finally, this weak production is also consistent with a detection rate below the sensitivity of the RGA system between pulses.

The results obtained in the three devices (JET-ILW, AUG and WEST) are consistent with the saturation of the N<sub>2</sub> reservoir prior to the potential ND<sub>3</sub> formation. Ammonia has been detected in AUG where the strongest N<sub>2</sub> injection has been performed whilst in JET-ILW, the ammonia detection is close to the detection limit.

Further experiments, with repetitive long discharges in steady state, with a higher radiating fraction (likely semi-detached plasma) with constant N<sub>2</sub> seeding would allow for clarifying the potential N<sub>2</sub> reservoir and the corresponding rate of ND<sub>3</sub> formation and release. Once again, the absence of active pumping coupled in USN with actively cooled PFCs in WEST appear as a benefit for an estimation of the N<sub>2</sub> reservoir that needs to be saturated prior to significant ND<sub>3</sub> formation as observed in AUG.



## **Acknowledgments**

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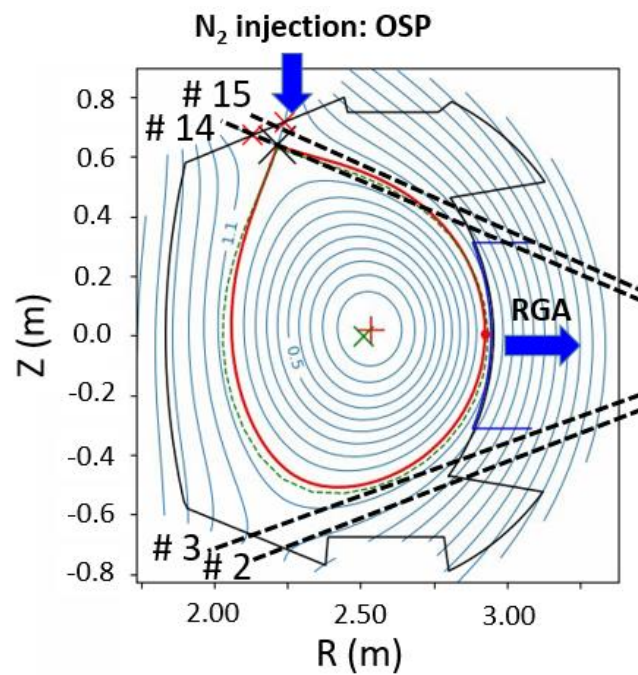
**Table I**

Summary of the N<sub>2</sub> and D<sub>2</sub> injection and particle balance for this series of long discharges.

Pulse number	# 55787	# 55789	# 55790	# 55792	# 55794
Plasma duration (s)	53	50.5	49	49.6	34.7
N <sub>2</sub> (0-3s) Pam <sup>3</sup>	0.134	0.187	0	0.161	0.205
N <sub>2</sub> inj. rate (Pam <sup>3</sup> s <sup>-1</sup> ) (Ns <sup>-1</sup> ) (window)	0	0.1 4.8x10 <sup>19</sup> (10-40s)	0.18 8.7x10 <sup>19</sup> (10-45s)	0.22 1.1x10 <sup>20</sup> (10-45s)	0.2 9.7x10 <sup>19</sup> (10-35s)
N <sub>2</sub> (Pam <sup>3</sup> ) injected & (N)	0	2.46 (1.18x10 <sup>21</sup> )	5.48 (2.64x10 <sup>21</sup> )	6.32 (3.05x10 <sup>21</sup> )	4.39 (2.12x10 <sup>21</sup> )
N <sub>2</sub> (Pam <sup>3</sup> ) pumped (%)	-	0.9 36	2.1 38	2.0 32	3.0 68
D <sub>2</sub> injected (Pam <sup>3</sup> ) (~Rate Pam <sup>3</sup> s <sup>-1</sup> )	11.6 (0.2-0.1)	11.6 (0.2-0.1)	11.2 (0.2-0.1)	9.5 (0.2-0.1)	9.76 (0.1)
D <sub>2</sub> (Pam <sup>3</sup> ) pumped (%)	9.5 82	9.1 78	8.9 79	9.0 94	8.1 83

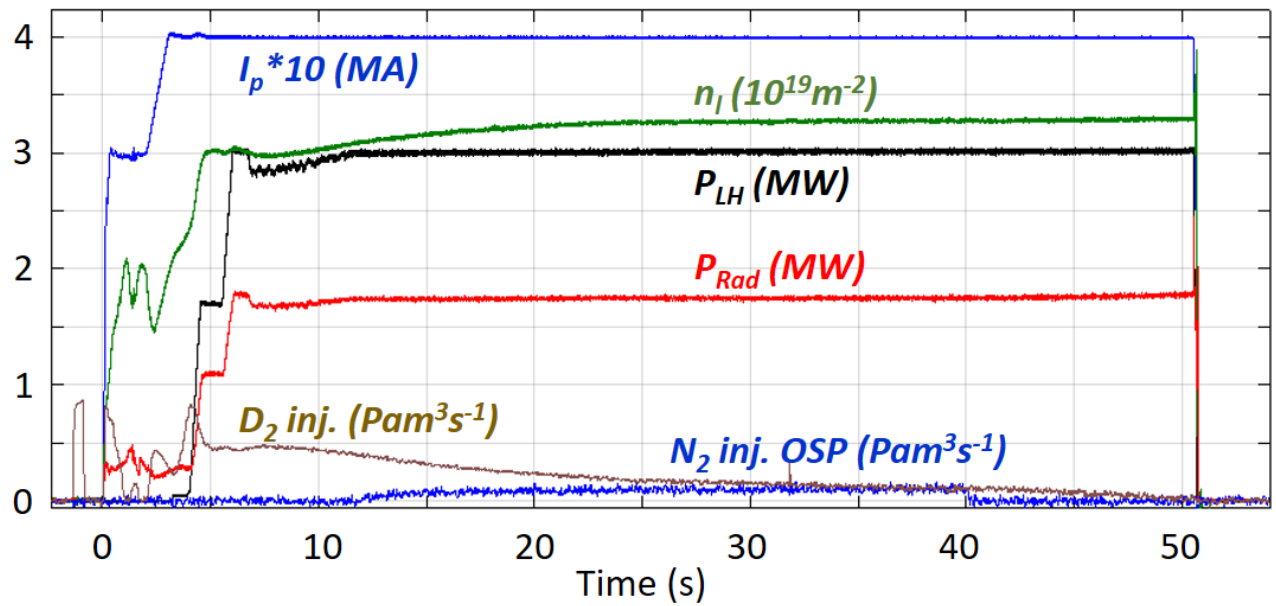
**Figure 1**

Poloidal cross section of the USN plasma configuration (#55789 @15.42s) with the location of  $N_2$  injection in the region of the OSP. The Residual Gas Analyser (RGA) used for the gas balance analysis is located in the mid-plane, whilst the  $D_2$  is also injected through the mid-plane (different port as the RGA) with a feedback control for keeping density constant over the entire plasma duration. The bolometer tracks probing the edge plasma in the OSP region (# 14 and # 15) and the lower part of the plasma (#2 and #3) are also shown.



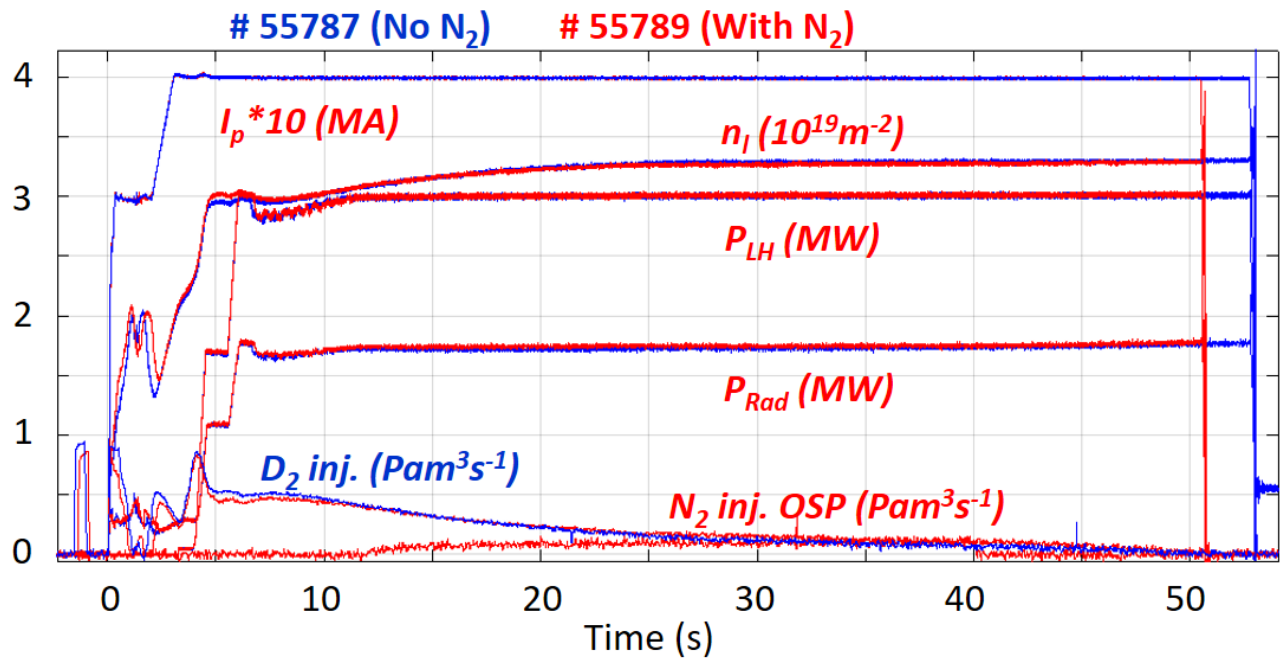
**Figure 2**

Main plasma parameters Plasma current,  $I_p$ , linear density,  $n_l$ , Lower hybrid power,  $P_{LH}$ , Radiated power,  $P_{rad}$ ,  $D_2$  and  $N_2$  injection rates for the pulse # 55789 which is representative of the series. For all these discharges, a steady state is reached from 25-30s up to the end of the discharge.



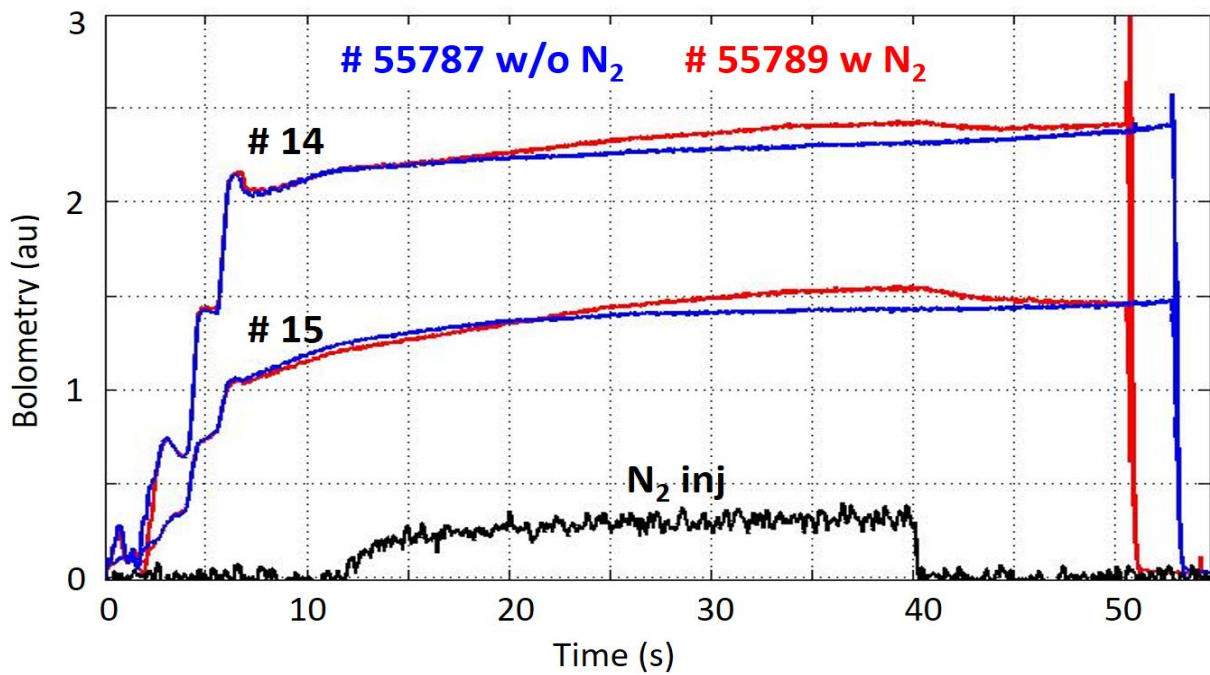
**Figure 3:**

Comparison of the main plasma parameters ( $I_p$ ,  $n_i$ ,  $P_{LH}$ ,  $P_{rad}$ ,  $D_2$  and  $N_2$  injection rates) for two long discharges without  $N_2$  injection (blue # 55787) and with  $N_2$  injection (red # 55789).



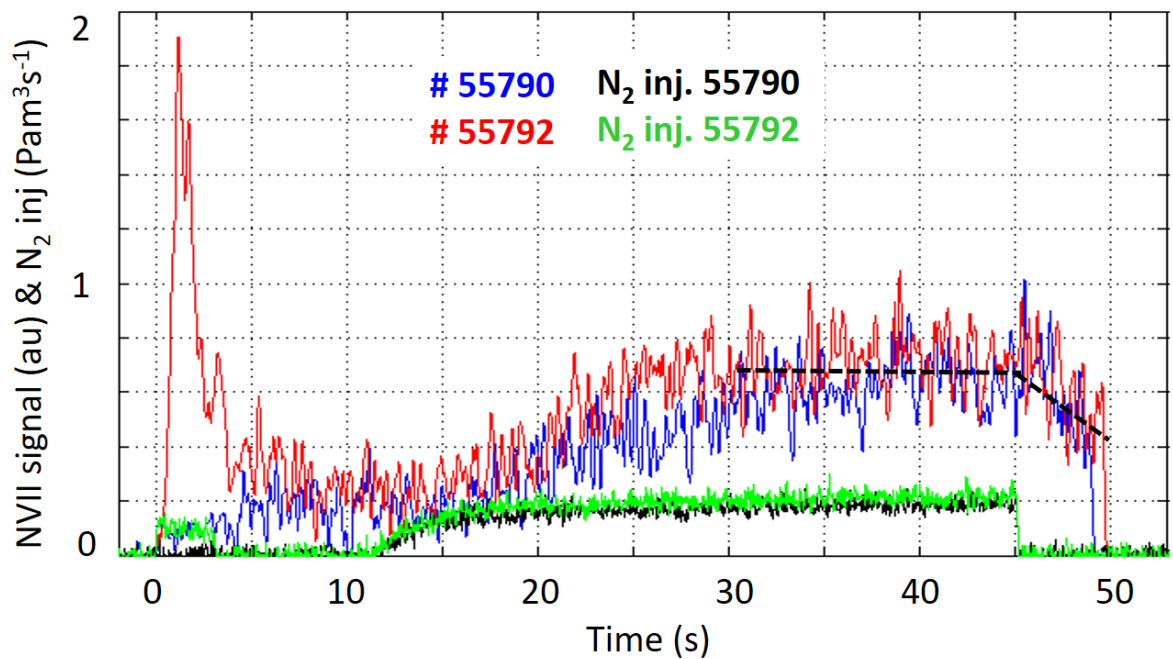
**Figure 4**

Time evolution of the two upper tracks of the bolometry (# 14 and # 15 – see figure 1) probing the edge plasma in the OSP region for a discharge without N<sub>2</sub> injection (# 55787 in blue) and with N<sub>2</sub> injection (# 55789 in red). N<sub>2</sub> injection @0.1 Pam<sup>3</sup>s<sup>-1</sup> is shown for pulse #55789. An increase of the bolometry signal by ~8% is observed only on these tracks whilst they recover their initial value as the injection is stopped.



**Figure 5**

NVII signal in the UV range @ 24.8 Å as a function of time for the discharges # 55790 (b) and # 55792 (r) and respective N<sub>2</sub> injection rates (black and green). For the pulse # 55790, following the first strong N<sub>2</sub> injection during 30s (pulse # 55789), no N<sub>2</sub> is injected at the beginning of the discharge. No NVII signal is observed in this early plasma phase contrary to pulse 55792 where N<sub>2</sub> is injected in the early plasma phase (green signal from 0 to 3s). The steady state phase of the NVII signal is clearly observed for t>30s whilst it drops as the N<sub>2</sub> injection is stopped.

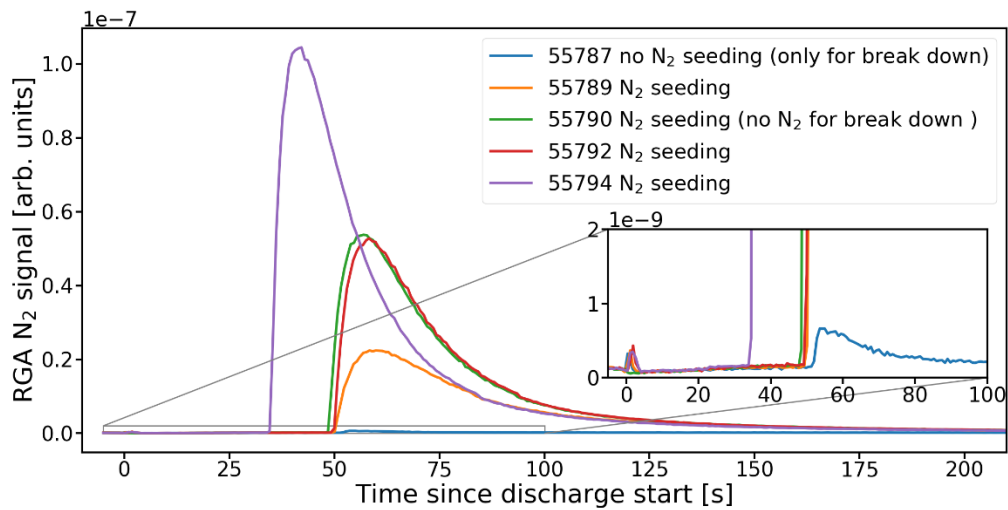




**Figure 6**

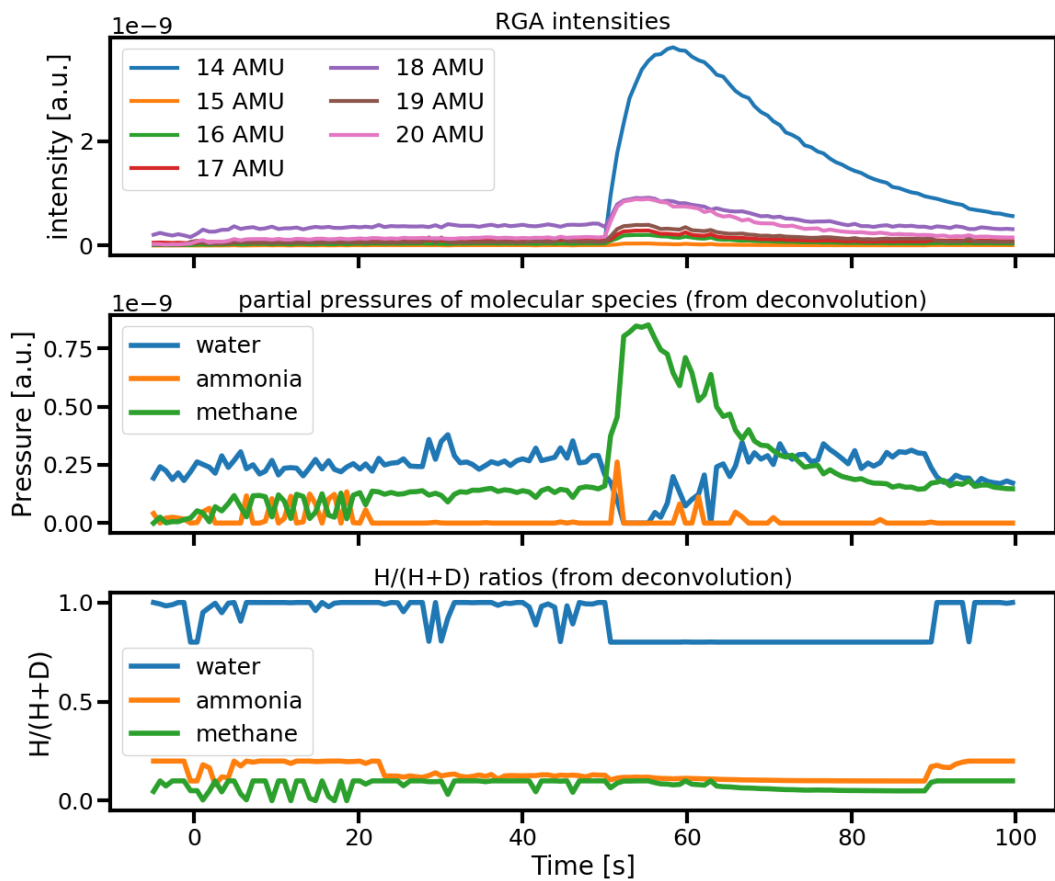
Time evolution of the Mass 28 ( $N_2$ ) recorded by the RGA in the mid-plane for the series of discharges (plasma from 0 to 50s range, except for # 55794 from 0 to 35s). The increase in the mass 28 signal with increasing discharge number can be attributed to the stronger seeding, but for the last pulse (# 55794) of this series, strong MHD activity occurred that could also explain the higher recovery due to different/enhanced plasma wall interaction with the potential  $N_2$  reservoir.

Insert, zoom on the time evolution of the mass 28 during the plasma and the early phase following the plasma end. This clearly demonstrates that, compared to the recovery phase, a negligible amount of  $N_2$  is pumped during the pulse.



**Figure 7**

Time evolution of the mass 20 ( $\text{ND}_3$ ,  $\text{CD}_4$  and  $\text{D}_2\text{O}$ ) measured in the RGA for the pulse # 55792 which contained the most nitrogen. There is neither  $\text{ND}_3$  detected during the pulse (0-50s) nor during the recovery and outgassing phase following the plasma ( $t > 50\text{s}$ ).



**Figure 8**

Time traces of the D<sub>2</sub> pressure for the pulses #55787 (m), #55792 (b) and partial pressure of N<sub>2</sub> (g) for the pulse #55792. For the two pulses, the D<sub>2</sub> pressures are very close and behave as  $t^{-0.7}$ , whilst the N<sub>2</sub> (g) pressure has to be adjusted with a law  $\propto t^{-1.6}$ .

Insert, for discharge # 55792 showing the maximum D<sub>2</sub> (b) pressure reached @53s and the maximum N<sub>2</sub> pressure (g) at @58s.

