



HAL
open science

Long discharges in a steady state with D 2 and N 2 on the actively cooled tungsten upper divertor in WEST

T. Loarer, T. Dittmar, E. Tsitrone, R. Bisson, C. Bourdelle, S. Brezinsek, J. Bucalossi, Y. Corre, L. Delpech, C. Desgranges, et al.

► To cite this version:

T. Loarer, T. Dittmar, E. Tsitrone, R. Bisson, C. Bourdelle, et al.. Long discharges in a steady state with D 2 and N 2 on the actively cooled tungsten upper divertor in WEST. Nuclear Fusion, 2020, 60 (12), pp.126046. 10.1088/1741-4326/abb919 . hal-03046790

HAL Id: hal-03046790

<https://amu.hal.science/hal-03046790v1>

Submitted on 20 Apr 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Long discharges in steady state with D₂ and N₂ on the actively cooled tungsten upper divertor in WEST

T Loarer¹, T Dittmar², E Tsitrone¹, R Bisson³, C Bourdelle¹, S Brezinsek², J Bucalossi¹, Y Corre¹, L Delpech¹, C Desgranges¹, G De Temmerman⁴, D. Douai¹, A Ekedhal¹, N Fedorczak¹, A Gallo¹, J Gaspar⁵, J Gunn¹, M Houry¹, P Maget¹, R Mitteau¹, P Moreau¹ and WEST team*

¹ CEA IRFM, F-13108 St Paul Les Durance, France

² Forschungszentrum Jülich GmbH, Institut für Energie und Klimaforschung – Plasmaphysik, Partner In the Trilateral Euregio Cluster, 52425 Jülich, Germany

³ Aix-Marseille University, CNRS, PIIM, Marseille, France

⁴ ITER Organization Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

⁵ Aix Marseille University, CNRS, IUSTI, Marseille, France

* See <http://west.cea.fr/WESTteam>
thierry.loarer@cea.fr

Abstract

Nitrogen (N₂) 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 N₂ with hydrogen isotopes can lead to the formation of tritiated ammonia (NT₃). 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 N₂ seeding from the outer strike point region have been performed on the upper actively cooled divertor. In the absence of active pumping, the N₂ balance shows a steady state retention during the plasma whilst partially (~35%) released in between discharges. Although a significant amount of N₂ (18.65 Pam³) has been injected, the wall still exhibits N₂ pumping capabilities. In these conditions, as far as this N₂ reservoir is not saturated, there is not enough N available for reaching the detectable threshold of ND₃ 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 N₂ 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 MWm^{-2} in steady state and transiently 20 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 N_2 with hydrogen isotopes can lead to tritiated ammonia (NT_3) as well as ND_x and 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 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 N₂ 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 N₂ injection and the potential formation of ammonia (ND₃). The objective of the reported experiments is to study the pumping behaviour of N₂ with metallic PFCs and ammonia formation due to the N₂ 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 N₂ seeding have been carried out in WEST for assessing the N₂ 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 N₂ 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⁻²) 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⁻² 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 (D₂) discharges in the range of 50s in steady state have been performed in the USN configuration with constant N₂ injection up to 35s from the outer strike point region (OSP) for assessing the N₂ particle balance and the resulting potential ND₃ 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 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 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 Pam^3 of D_2 ($4.58 \times 10^{21} \text{ D}$ & $4.58 \times 10^{21} \text{ e}^-$) and 6.32 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°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 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 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 N_2 injection remains only as a “local” effect in the recycling area.

Going deeper in the plasma, the 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 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 N_2 injection and showing that the early NVII signal peak is not observed confirming the absence of N_2 legacy from previous 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 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 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 N_2 injection on the radiation pattern (bulk and edge), and confirmed by the Langmuir probes and the IR measurements.

The N₂ 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 1.0x10⁻³ Pa range for all the discharges and always with D₂ as the dominant species. For all these discharges, the same behaviour of N₂ is observed more or less independently of the amount injected. **Figure 6** shows the time evolution of the mass 28 (N₂) recorded by the RGA during the plasma and the recovery phases for the five discharges of the series; # 55787 being run without N₂ injection during the heating phase. This clearly shows that compared to the amount injected a totally negligible amount of N₂ is pumped during the pulse through the mid-plane; this point is discussed later in the paper. After the pulse, the N₂ 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 N₂ 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] N₂ 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 ND₃ 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 N₂ recovery after the pulse due to the disruption.

During the four discharges cumulating more than 3 minutes of plasma, N₂ 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 Pam³s⁻¹ for a total duration of 125s for investigating both the potential legacy of N₂ injection on plasma performances and the formation of ND₃ 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 N₂ 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 D₂ and N₂ species can be expressed as:

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

where Γ_{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 (D₂ and N₂) 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 D₂ and N₂ whilst the “traces” of H₂ and H₂O 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 0.5-1.0x10⁻³ Pa range. With a total pumping speed of 9.8m³s⁻¹ for the D₂, this leads to a maximum pumping rate of 0.01 Pam³s⁻¹ by far less and negligible compared to the D₂ injection rate in the range ~0.2 Pam³s⁻¹. The same conclusion results for N₂ 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 Pam³s⁻¹ independently of the cumulated amount of D₂ and N₂ 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 N₂ injection (# 55787) and the pulse (# 55792) with the strongest N₂ injection. For the pulse # 55787 (duration of 53s) 11.6Pam³ of D₂ has been injected and for the pulse # 55792 (duration of 49.3s), 9.49 Pam³ of D₂ and 6.32Pam³ of N₂ have been injected. Except for the N₂ 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 Pam^3 of D_2 have been pumped that have to be compared to the 11.6 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 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 ~ 25 min (See **figure 8**). Based on this fit, the D_2 balance shows that 9.0 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 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°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 Pam^3 , corresponding to 70% of the amount injected (4.39 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 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), 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 Pam^3 , is totally negligible compared to the 2.46 to 6.32 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 N_2 is injected during this early plasma phase, no N_2 is detected at all even if 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 N_2 injected during the previous plasmas.

These results also support the fact that the N_2 reservoir is primarily located close to the OSP region where the N_2 is injected. Indeed, when compared to long discharges performed in the same conditions with N_2 injected through the mid-plane, N_2 was detected by the RGA during the plasma meaning that all this 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) 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 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 600m^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 80m^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 (10m^2). However, the upper divertor is made of copper with a W coating

of 15-20 μm . 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 ~ 15 -20 pulses, this N₂ 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 N₂ 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 N₂ 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 N₂ retention in the range of 50% (same range observed in WEST) and also a significant increase in D₂ retention compared to reference experiments. Whilst no effect of N₂ injection has been noticed at all on the D₂ balance in WEST, according to the author, this “extra” D₂ retention in JET-ILW can be attributed to the N₂ seeding through ammonia formation corresponding to roughly 15% of the injected N atoms converted to ND₃. 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 ND₃ 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 N₂ 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 N₂ 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 ND₃ 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 N₂ and D₂ 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 ND₃ 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 N₂ 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 N₂ and the ND₃ formed to migrate up to the mid-plane. However, this means that a significant amount of ND₃ 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 (9.0×10^{21} N) can appear low compared to JET-ILW and AUG with respectively 3.62×10^{22} and 4.05×10^{22} N injected, it is worth reminding that the absence of N₂ pumping in WEST allows for all the N₂ injected to be dissociated (and therefore potentially forming ND₃). In both JET-ILW and AUG a non-negligible part (always very difficult to assess) of the injected N₂ 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 N₂ 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 ND₃ formation in the sub-divertor area particularly when compared to the non-seeded case. However, it could be worth repeating these experiments with N¹⁵ 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 N₂ seeding from the OSP region cumulating 237 s of plasma (~4min). A total of 18.65 Pam³ of N₂ has been injected in 4 consecutive discharges through the OSP during up to 35s and with injection rate of 0.21 Pam³s⁻¹. For all these experiments with N₂ 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 N₂ whilst no saturation is observed for duration in the range of 35s. The D₂ 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 D₂ retention and recovery does not appear to be influenced by the N₂ injection. The N₂ 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 N₂ wall pumping over the seeded duration could have been expected. This has not been the case at all and since no legacy from the N₂ injection has been observed on the following pulse, this shows that the N₂ reservoir is not saturated.

Considering the N₂ 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 N₂ 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 ND₃ production. Prior to this saturation, no or not enough N is available for ND₃ formation, explaining that no ND₃ 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 N₂ reservoir prior to the potential ND₃ formation. Ammonia has been detected in AUG where the strongest N₂ 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 N₂ seeding would allow for clarifying the potential N₂ reservoir and the corresponding rate of ND₃ 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 N₂ reservoir that needs to be saturated prior to significant ND₃ formation as observed in AUG.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 63253. The views and opinions expressed herein do not necessarily reflect those of the European Commission or of the ITER Organization.

References

- [1] “ITER Research Plan within the Staged Approach”, ITER Technical Report ITR-18003 available at: <https://www.iter.org/technical-reports>.
- [2] R Pitts et al., Nuclear Materials and Energy 20 (2019) 100696.
- [3] A Kallenbach et al., Plasma Phys. Control. Fusion 55 (2013) 124041
- [4] C Giroud et al., Plasma Phys. Control. Fusion 57 (2017) 035004.
- [5] R Walker et al., Fusion Engineering and Design, 124 (2017) 892-895.
- [6] J Bucalossi et al., Fusion Engineering and Design, 89 (2014) 907–912.
- [7] C Bourdelle et al., Nuclear Fusion 55 (2015) 063017 (15pp).
- [8] M Oberkopfer et al., Journal of Nuclear Materials, Vol 438, July 2013, pages S258-S261.
- [9] A Drenik et al., Nuclear Fusion 59 (2019) 046010 (18pp).
- [10] T Dittmar et al., Physica Scripta T171 (2020) 014074 (5pp) <https://doi.org/10.1088/1402-4896/ab753f>
- [11] D Neuwirth et al., Plasma Phys. Control. Fusion 54 (2012) 085008 (10pp) **54** 085008
- [12] G Meisl et al., New Journal of Physics 16 (2014) 093018

Table I

Summary of the N₂ and D₂ 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 ₂ (0-3s) Pam ³	0.134	0.187	0	0.161	0.205
N ₂ inj. rate (Pam ³ s ⁻¹) (Ns ⁻¹) (window)	0	0.1 4.8x10 ¹⁹ (10-40s)	0.18 8.7x10 ¹⁹ (10-45s)	0.22 1.1x10 ²⁰ (10-45s)	0.2 9.7x10 ¹⁹ (10-35s)
N ₂ (Pam ³) injected & (N)	0	2.46 (1.18x10 ²¹)	5.48 (2.64x10 ²¹)	6.32 (3.05x10 ²¹)	4.39 (2.12x10 ²¹)
N ₂ (Pam ³) pumped (%)	-	0.9 36	2.1 38	2.0 32	3.0 68
D ₂ injected (Pam ³) (~Rate Pam ³ s ⁻¹)	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 ₂ (Pam ³) 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.

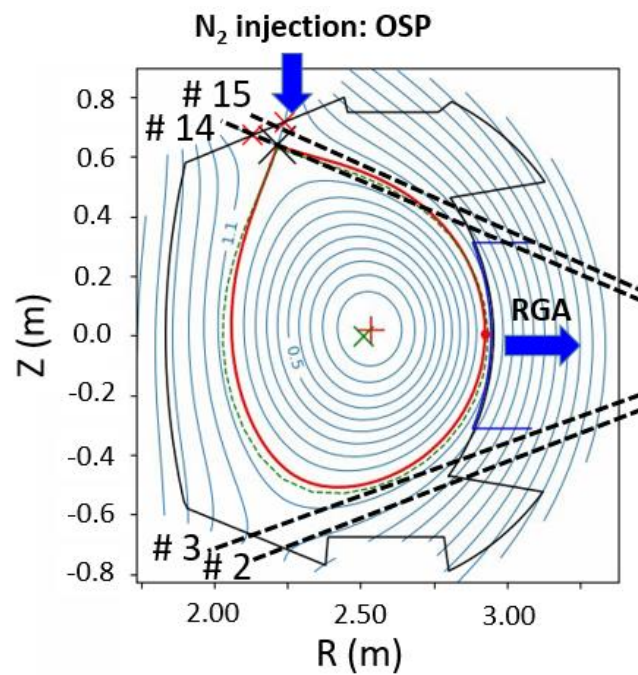


Figure 2

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.

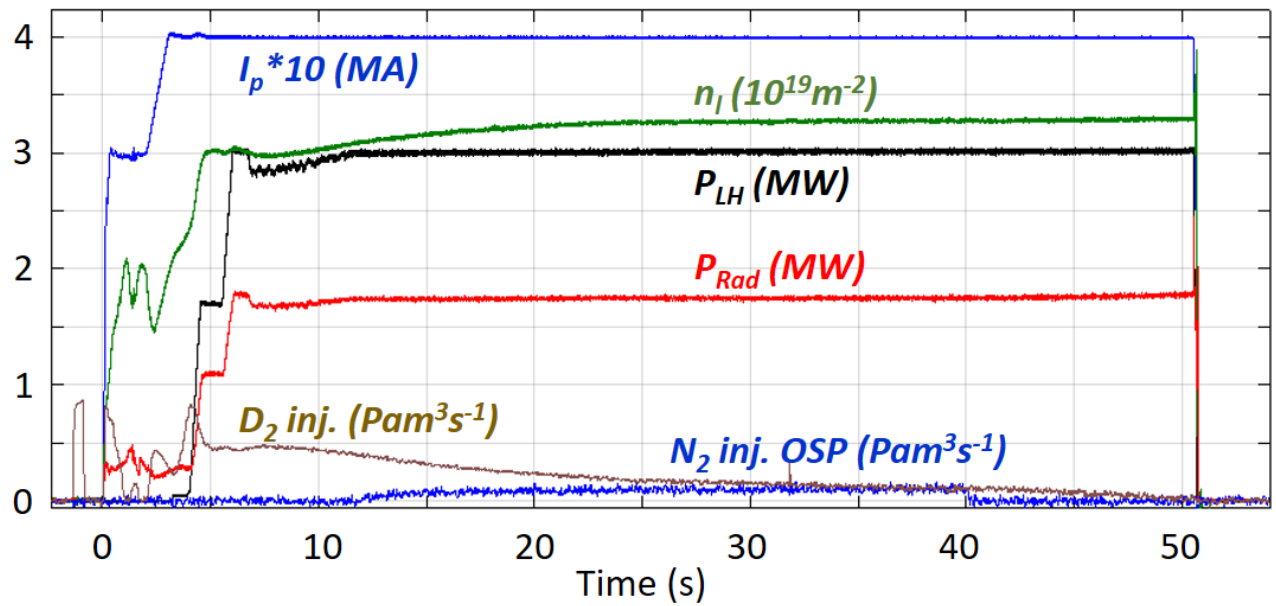


Figure 3:

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).

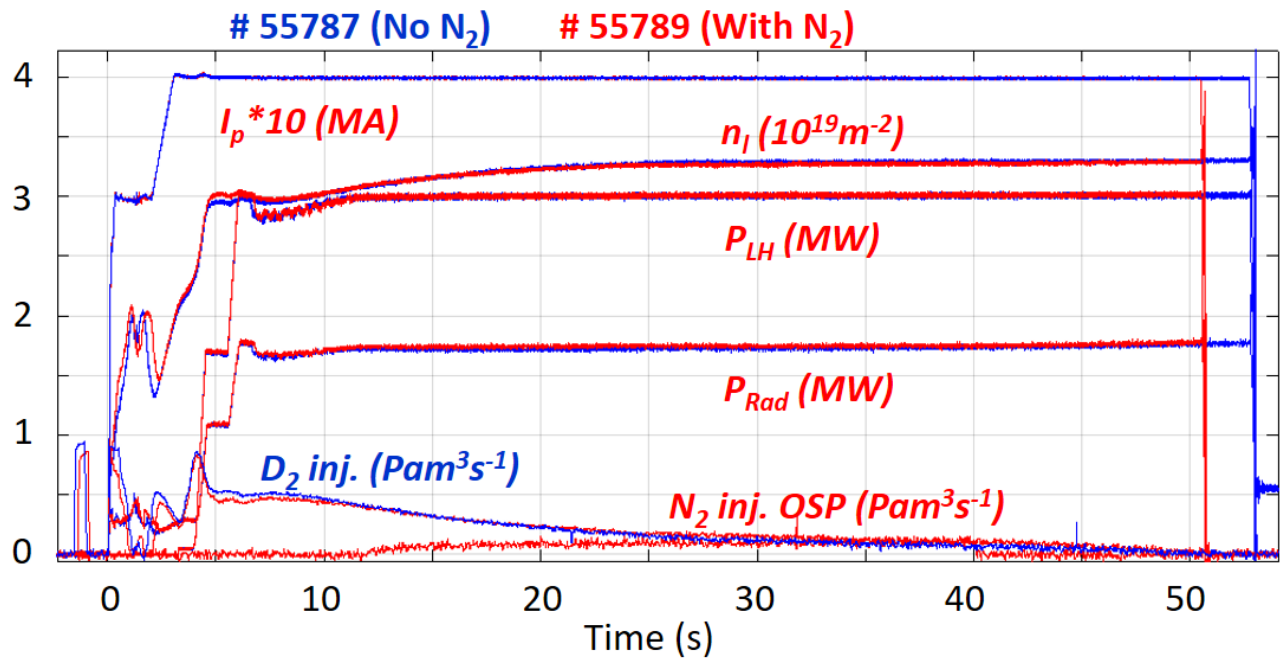


Figure 4

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 N₂ injection (# 55787 in blue) and with N₂ injection (# 55789 in red). N₂ injection @0.1 Pam³s⁻¹ 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.

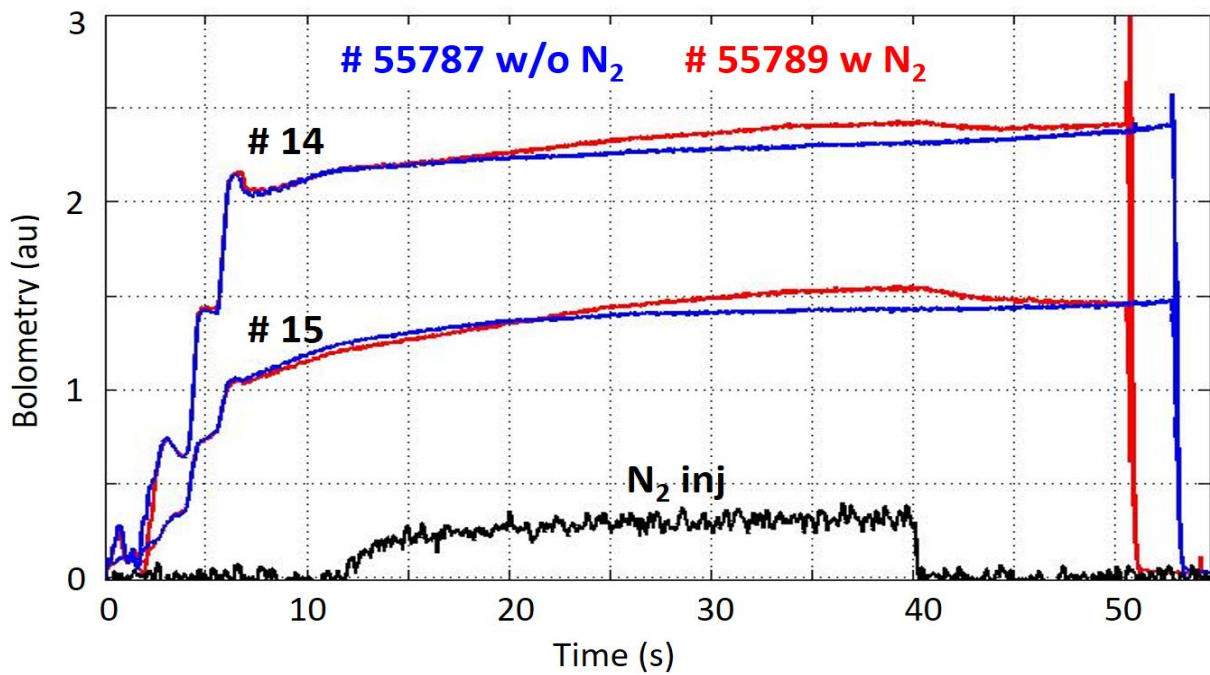


Figure 5

NVII signal in the UV range @ 24.8 Å as a function of time for the discharges # 55790 (b) and # 55792 (r) and respective N₂ injection rates (black and green). For the pulse # 55790, following the first strong N₂ injection during 30s (pulse # 55789), no N₂ is injected at the beginning of the discharge. No NVII signal is observed in this early plasma phase contrary to pulse 55792 where N₂ 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 N₂ injection is stopped.

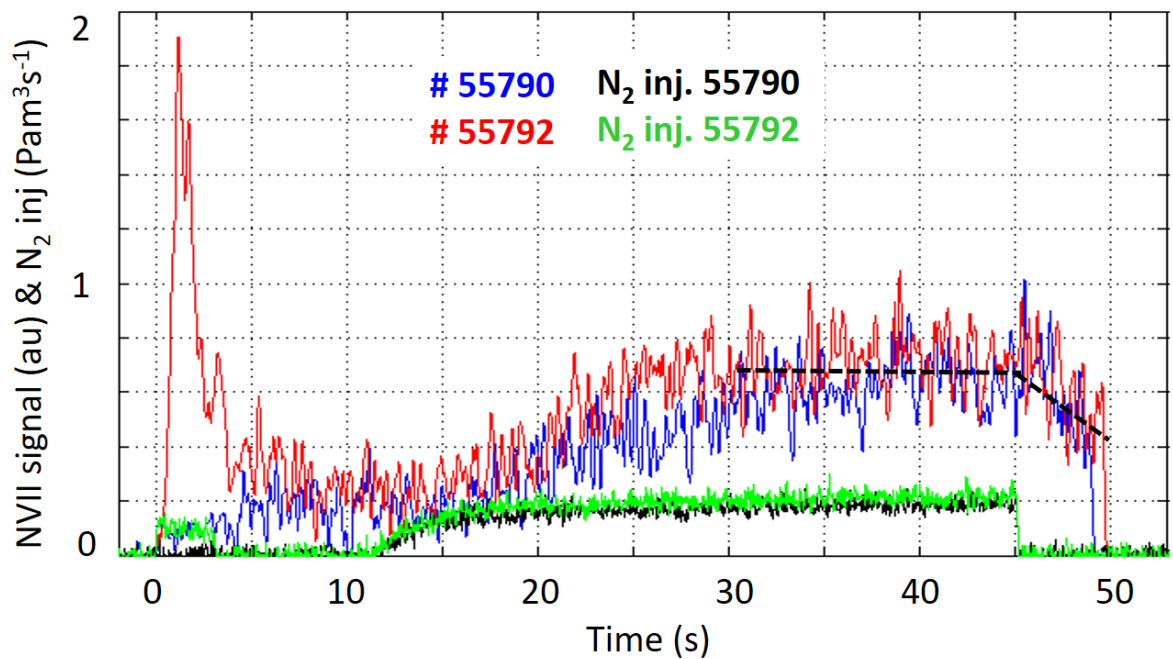


Figure 6

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.

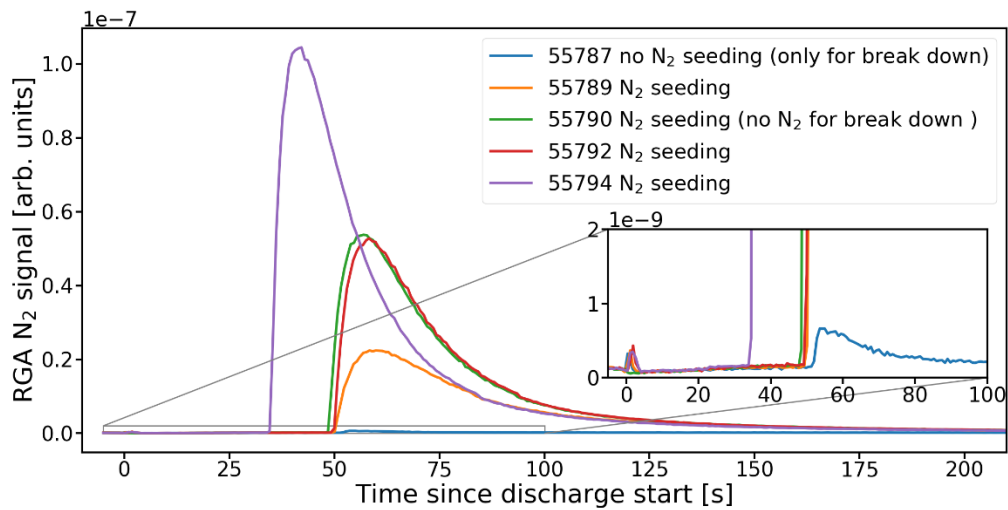


Figure 7

Time evolution of the mass 20 (ND_3 , CD_4 and D_2O) measured in the RGA for the pulse # 55792 which contained the most nitrogen. There is neither ND_3 detected during the pulse (0-50s) nor during the recovery and outgassing phase following the plasma ($t > 50\text{s}$).

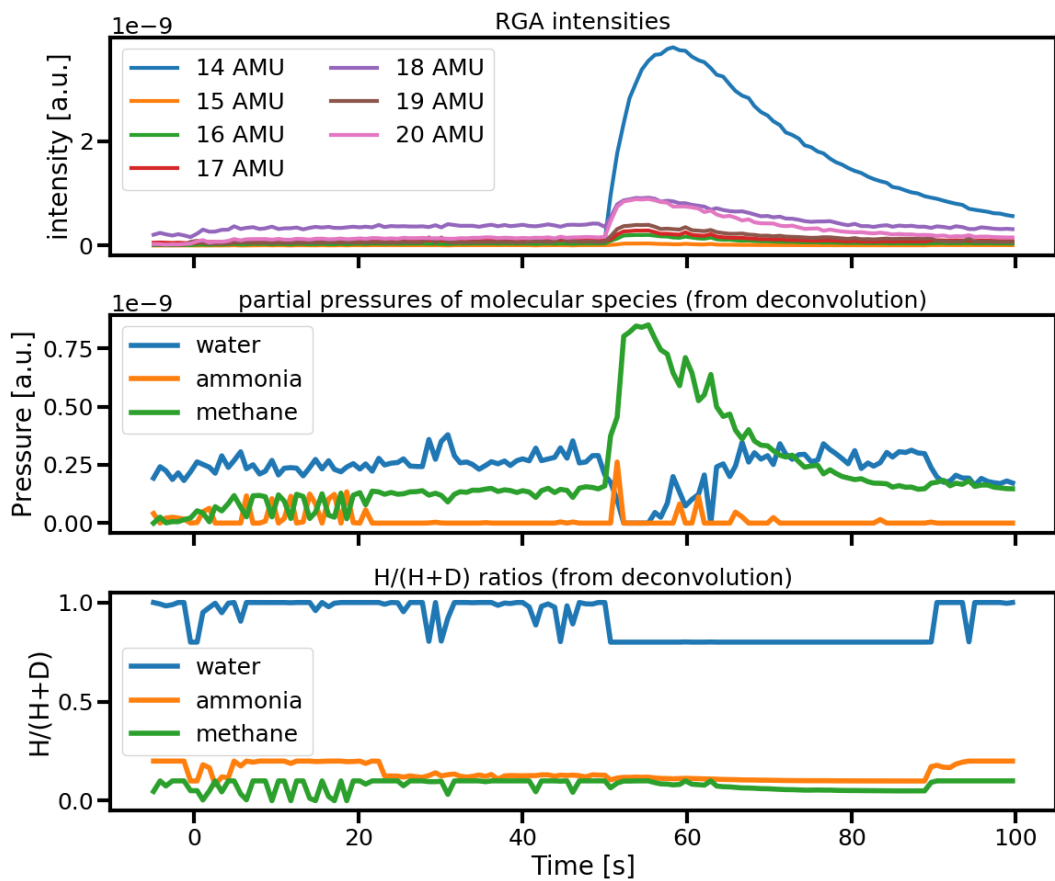


Figure 8

Time traces of the D₂ pressure for the pulses #55787 (m), #55792 (b) and partial pressure of N₂ (g) for the pulse #55792. For the two pulses, the D₂ pressures are very close and behave as $t^{-0.7}$, whilst the N₂ (g) pressure has to be adjusted with a law $\propto t^{-1.6}$.

Insert, for discharge # 55792 showing the maximum D₂ (b) pressure reached @53s and the maximum N₂ pressure (g) at @58s.

