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Experimental evidence of enhanced recombination of a hydrogen plasma induced by nitrogen seeding in linear device Magnum-PSI

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\begin{abstract}
In this work we investigate the effects induced by the presence of nitrogen in a detached-like hydrogen plasma in linear plasma machine Magnum-PSI. Detachment has been achieved by increasing the background neutral pressure in the target chamber by means of H\textsubscript{2}/N\textsubscript{2} puffing and two cases of study have been set up, i.e. at 2 and 4 Pa. Achieved n\textsubscript{e} are ITER-relevant, i.e. above 10\textsuperscript{20} m\textsuperscript{-3} and electron temperatures are in the range 0.8–2 eV. A scan among five different N\textsubscript{2}/H\textsubscript{2} + N\textsubscript{2} flux ratios seeded have been carried out, at values of 0, 5, 10, 15 and 20%. A n\textsubscript{e} decrease while increasing the fraction of N\textsubscript{2} has been observed for both background pressures, resulting in a plasma pressure drop of \~30%. T remains constant among all scans. The peak intensity of NH*(A 3\underline{\Pi} → X 3\underline{\Sigma}−, \Delta v = 0) at 336 nm measured with optical emission spectroscopy increases linearly with the N\textsubscript{2} content, together with the NH\textsubscript{3} signal in the RGA. A further dedicated experiment has been carried out by puffing separately H\textsubscript{2}/N\textsubscript{2} and H\textsubscript{2}/He mixtures, being helium a poorly-reactive atomic species, hence excluding a priori nitrogen-induced molecular assisted recombination. Interestingly, plasma pressure and heat loads to the surface are enhanced when increasing the content of He in the injected gas mixture. In the case of N\textsubscript{2}, we observe an opposite behavior, indicating that N–H species actively contribute to convert ions to neutrals. Recombination is enhanced by the presence of nitrogen. Numerical simulations with two different codes, a global plasma-chemical model and a spatially-resolved Monte Carlo code, address the role of NH\textsubscript{x} species behaving as electron donor in the ion conversion with H\textsuperscript{+} by means of what we define here to be N-MAR i.e. NH\textsubscript{x}+ H\textsuperscript{+} \rightarrow NH\textsubscript{x}++ H, followed by NH\textsubscript{x}++ e\textsuperscript{−} \rightarrow NH\textsubscript{x}-1 + H. Considering the experimental findings and the qualitative results obtained by modelling, N-MAR process is considered to be a possible plasma-chemical mechanism responsible for the observed plasma pressure drop and heat flux reduction. Further studies with a coupled code B2.5-Eunomia are currently ongoing and may provide quantitative insights on the scenarios examined in this paper.

\end{abstract}

\section{Introduction}

Plasma detachment is characterized by a plasma pressure drop along the magnetic field lines towards the divertor target and by a significant reduction of the ion flux together with lower power loads \cite{1}. Detachment is characterized by a “roll-over” of the ion saturation current measured at the target \cite{2}. Such phenomena is achieved by a synergistic effect of radiative losses, momentum transfer from incoming ions to neutrals and volumetric recombination. Although it has been proposed that molecular-activated recombination (MAR), as well as three-body and radiative recombination, may play an important role for plasma detachment in linear devices \cite{3–5}, a limited contribution of MAR has been highlighted in tokamak divertor detachment \cite{6,7}. In this paper we focus specifically on the role of nitrogen and hydrogenated nitrogen molecules on the neutralization of atomic hydrogen ions and on the effects over plasma parameters. It has been observed \cite{8,9} that impurity seeding facilitates the realization of a detached plasma regime. Nitrogen is the current leading candidate for impurity seeding in ITER \cite{10}. The atomic and molecular processes led by N\textsubscript{2} injection in a divertor-like hydrogen plasma (n\textsubscript{e} > 10\textsuperscript{20} m\textsuperscript{-3}) is yet poorly understood. Linear devices have extensively contributed in understanding plasma detachment because of the good diagnostic accessibility and the capability of maintaining a detached plasma in a steady-state regime for a long time at a relatively low cost \cite{11}. The heat flux to the target is expressed as: \( q = \Gamma (\gamma T + E) \), with \( \Gamma \) the ion flux, \( \gamma \) the sheath heat transmission coefficient, and \( E \) the intrinsic ion potential.
energy (18.08 eV per atomic hydrogen ion). The cooling of plasma is not enough by itself to reduce the heat loads, given the ion’s potential released on the plate due to surface recombination process [12]. Volume recombination is needed to reduce the charged particle flux, converting ions to neutrals [13]. It is worth mentioning that the release of H₂ molecules in vibrational excited state from the target depends on the surface temperature and on the adopted material. Further insights on this phenomenon can be found in [14] and references therein. A newly-addressed aspect relative to plasma detachment is the concept of power limitation [15,16]. In a tokamak, the bulk of the particle source is located in the divertor in the vicinity of the target (the mean free path for neutral ionization is smaller than the typical divertor size). The energy for such ionization needs to be provided by power coming from further upstream. Impurities injection radiate away part of this power, typically further upstream from the recycling region. Hence, less power is available for ionization, causing an uplifting of the recombination front and the rollover of the target particle flux. In Magnum-PSI this is not the case, in fact there is a constant particle and energy flux coming from the source. The magnetically confined plasma goes throughout the source and middle chambers without significant power dissipation (differential pumping is designed to remove neutral particles along the beam path). During normal Magnum-PSI operation, even in attached-like scenarios, Tₑ is not sufficiently high to drive a relevant ionization source in the target chamber.

The scope of this work is to study the influence of different nitrogen concentrations on the plasma parameters in a detached plasma scenario in the upgraded linear plasma machine Magnum-PSI [17]. This is done by using Thomson Scattering (TS), Optical Emission Spectroscopy (OES), Residual Gas Analyser (RGA) and calorimetry. Numerical simulations have been used to provide qualitative explanation of the observed nitrogen-driven N-MAR processes. In a tokamak perspective, this paper focuses on highlighting the dominant recombination mechanisms occurring in the vicinity of the divertor target in a N₂-seeded detached hydrogen plasma.

2. Experimental set up and diagnostics

Linear machine Magnum-PSI is a unique plasma generator capable of mimic the foreseen plasma conditions of ITER divertor, i.e. Tₑ ≤ 5 eV, nₑ ≥ 10^{20} m⁻³ and particle flux up to 10^{24} m⁻² s⁻¹, leading to heat loads of about 10 MWM⁻² [18]. A detailed description of the design of the machine together with its capabilities can be found here [19]. In short, the machine is characterized by three different chambers, namely source chamber, heating and target chamber [20]. Differential pumping, together with skimmers located at the entrance of each chamber, separate these environments. In this way, plasma pressure is conserved throughout the entire beam, hence exposing the target to ITER-relevant plasma. Plasma is generated by means of a cascaded arc plasma source [21] located in the source chamber and is confined in the z direction towards the target by a superconducting magnet. The background pressure in the target chamber, during normal “attached” operation is ≈ 0.3 Pa. The target consists of a tungsten (W) plane circular target with a diameter of 3 cm and a thickness of 1 mm. Detached-like conditions are achieved by increasing the total background pressure in the target chamber, as will be explained in Section 3. Tₑ and nₑ have been diagnosed by means of TS, located at 3 cm in front of the target. A detailed description of the system can be found in [22]. For the analysis of nitrogen key-species in the plasma, a two-channel fiber-optic spectrometer (AvaSpec-ULS2048) with a bandwidth coverage between 299 and 579 nm has been used. Of particular interest for this work is the signal at 336 nm, corresponding to the NH⁺ (A^3Π → X^3Σ⁻⁻) transition. The location of OES is the same as TS i.e. 3 cm in front of the target. For the monitoring of ammonia, a residual gas analyser (SRS-RGA) has been adopted. It consists of an ionizer, a quadrupole mass filter and a detector. Peaks at m/q 15, 16 and 17 amu, corresponding to NH, NH₂ and NH₃ species, have been monitored in this study. To measure the heat loads onto the target surface, calorimetry has been used.

3. Plasma detachment in linear machine Magnum-PSI

Detachment of the plasma beam from the target is achieved by gas seeding in the target chamber hence increasing the overall background neutral pressure. In Fig. 1 is reported a background pressure scan of a H₂ plasma, from 0.3 to 16.5 Pa. Neutral pressure has been enhanced by puffing hydrogen in the target chamber. The dotted line corresponds to TS line of sight, while the straight line represents the target location.

In Fig. 1(a), where a typical attached plasma is depicted, light emission is observed predominantly in the vicinity of the target. This is interpreted as ion recycling at the target, followed by electron-impact excitation of the neutral particles released from the surface. When increasing the neutral background pressure up to ≈ 6 Pa i.e. 1(b), (c) and (d), we observe a shift of the light emitted from the vicinity of the target to throughout the portion of observed plasma beam. Increasing the pressure further (1(e) and 1(f)) leads to a visible extinction of the plasma beam before reaching the target. The experimental detached-like scenarios chose for this work correspond to 2 and 4 Pa, where plasma parameters are suitable for recombination i.e. Tₑ < 2 eV and nₑ > 5 x 10^{19} m⁻³.

In Fig. 2 total static plasma pressure, calculated as P₀ = 2kTₑnₑ (assuming Tₑ = Tᵢ), is plotted as a function of the background neutral pressure in the vessel. By increasing the amount of gas in the chamber up to 16 Pa, plasma pressure drops almost to zero. We address such behavior to be mostly due to volumetric recombination of incoming hydrogen ions. The effect of radiative cooling alone on the plasma pressure drop is excluded to be dominant in Magnum-PSI detached-like scenarios because of the constant power input coming from the plasma source. Moreover, given the plasma pressure conservation along the beam [23], no power starvation phenomena are expected to be dominant in this environment. Regarding H₂-driven volume recombination, MARS are initiated by hydrogen molecules in vibrational excited states and constitute of two different two-step reaction paths, i.e.:

\[
\begin{align*}
H_2(v) + H^+ &\rightarrow H^+_2 + H \\
H^+_2 + e^- &\rightarrow H^+ + H \\
H_2(v) + e^- &\rightarrow H^- + H \\
H^- + H^+ &\rightarrow H_2 + H \\
\end{align*}
\]
Reaction (1) is initiated by ion conversion and is followed by dissociative recombination, while the first step of reaction (2) is dissociative attachment, which is followed by mutual neutralization. In both cases, H$^+$ is effectively converted to neutral. In the plasma environment of this case of study, molecular ion H$_3^+$ is poorly produced due to very efficient dissociative recombination of its ionic primitive H$_2^+$ [24].

In a nitrogen-seeded environment we expect plasma chemistry to be influenced by the presence of N$_x$(H$^+$) species. In the next paragraph, the effect on plasma parameters caused by the addition of different H$_2$/N$_2$ ratios puffed in the target chamber is investigated and discussed.

4. Nitrogen seeding experiments

Neutral background pressure has been enhanced in the target chamber by means of two remote controlled seeding valves, one for H$_2$ and the other for N$_2$, with a flow rate up to 2.4 × 10$^{-4}$ m$^3$s$^{-1}$. The H$_2$ gas flow through the source is fixed at 1.16 × 10$^{-4}$ m$^3$s$^{-1}$, the current at 120 A and the applied magnetic field is 1.2 T. The target plate is kept perpendicular to the plasma beam. The RGA is placed at the end of the pump tube that connects the target chamber with the roots pump. A baseline scenario has been defined experimentally and it represents the “attached” case. No molecular gas has been introduced in the vessel, with pumping rate at 100%, resulting in a background pressure of 0.3 Pa. Peak plasma parameters obtained in that case are $T_e = 3.48$ eV and $n_e = 1.3 \times 10^{20}$ m$^{-3}$. Subsequently, two detached cases of study have been set up: background neutral pressure has been kept fixed at 2 and 4 Pa. For each case, a scan consisting of different nitrogen flux ratios of puffed gas has been carried out for $\frac{[N_2]}{[N_2]+[H_2]} = 0$, 5, 10, 15, 20 %. In Fig. 3 electron density and temperature profiles are reported for each seeding ratio at background pressures of 2 and 4 Pa.

The full-width-half-maximum (FWHM, averaged over all H$_2$/N$_2$ seeding shots) is 16.7 mm at 4 Pa and 15 mm at 2 Pa. This discrepancy is due to the higher neutrals content which leads to an enhancement of elastic collisions frequency, thus increasing diffusion perpendicularly to the plasma beam. This effect in linear plasma machines has been recently investigated by means of Soledge2D-Eirene simulations in [18]. The reduction of the parallel transport due to momentum-transfer processes leads to an increased radial diffusion, resulting in a broadening of the beam [25]. When looking at the different H$_2$/N$_2$ puffing ratios, a clear trend is observed in both cases, with $n_e$ decreasing while increasing the content of N$_2$ in the puffed gas mixture. Peak values of electron density decrease from $2.2 \times 10^{20}$ m$^{-3}$ to $1.3 \times 10^{20}$ m$^{-3}$ between N$_2 = 0\%$ and N$_2 = 20\%$ for the 2 Pa case and from $2.1 \times 10^{20}$ m$^{-3}$ to $1.3 \times 10^{20}$ m$^{-3}$ for the 4 Pa one. Electron temperatures peak values were 1.8 eV at 2 Pa and 1 eV at 4 Pa. $T_e$ remains almost constant among all the different seeding scenarios. Given that $T_e$ is almost constant among the impurity content scan, the heat flux is governed by the particle flux. The significant $n_e$ reduction is hypothesized to be caused by additional recombination mechanisms introduced by the presence of nitrogen, which act as electrons sinks.

Recent theoretical work carried out by our group [26] highlighted newly-proposed plasma chemistry recombination paths, named N-MAR, occurring in a detached-like high-density (n$_e > 10^{20}$ m$^{-3}$) low-temperature (T$_e < 2.5$ eV) hydrogen plasma in the presence of nitrogen. Such mechanisms have been found to be important converting hydrogen ions to neutrals by a two-step process as follows:

\[
\text{NH}_x + H^+ \rightarrow \text{NH}_x^+ + H \text{ Ionconversion} \\
\text{NH}_x^+ + e^- \rightarrow \text{NH}_x(-1) + H \text{ Dissociative recombination}
\]  

They are initiated by ion conversion between NH$_x$ with 1 ≤ x ≤ 3 and H$^+$. The products NH$_x^+$ promptly undergo dissociative recombination, the ion conversion being the rate determining step of N-MAR. Particular importance is attributed to NH radical, which acts efficiently as electron donor in the ion conversion with H$^+$. Extensive plasma chemistry simulations by using global modelling [27] with Plasimo code [28] have been set up corresponding to the experimental scenarios showed in Fig. 3.

In global models the power is assumed to be homogeneously distributed and the plasma is uniform among the simulated volume. The outcome is collected by solving a system of coupled differential equations i.e. the quasi – neutrality, the energy balance and the particle balance. Those solutions describe the evolution of charged and neutral species as a function of time. Although limitations posed by a zero-dimensional code, global models allow one to implement large plasma chemical datasets. Specifically, a model including 20 species and 106 processes has been set-up to obtain a reduced set of plasma chemical reactions to be then implemented in Euinomia i.e. a spatially-resolved Monte Carlo code suited for simulations of linear plasma devices. Interestingly, the molecular-driven recombination paths of H$^+$ calculated by the code points out the relevance of NH radical as electron donor in the ion conversion with H$^+$. (70%, Fig. 4). The formation of NH occurs mostly in the plasma volume via electron-impact dissociation of NH$_3$.

The rate coefficients for the N--H$_2$ driven processes together with
hydrogenic MAR [24] are plotted as a function of electron temperature with \( n_e = 1 \times 10^{20} \text{ m}^{-3} \).

When looking at the reaction rate of hydrogen MAR compared to N-MAR, one can promptly see that \( \text{N}_2 \)-related process are more effective than the only-\( \text{H}_2 \) mechanisms. It appears to be clear that nitrogen-related species play a role in the conversion of ions to neutrals. This is also in accordance with the high proton affinity of \( \text{NH}_3 \), i.e. 854 kJ/mol [29].

The most relevant \( \text{H}_2 \)-\( \text{N}_2 \) plasma chemical processes have been selected from the above-mentioned model and, subsequently, implemented in EUNOMIA, a spatially-resolved Monte Carlo code suited for simulating the neutral inventory in linear plasma machines [30]. MAR and N-MAR convert ion-electron pairs to neutral atoms, yielding an increased production of \( \text{H} \). Simulations of the 2 Pa case depicted in Fig. 3 have been carried out and \( \text{H} \) density has been monitored to evaluate recombination efficiency occurring in each experimental \( \text{H}_2/\text{N}_2 \) seeding case. In Eunomia standalone, a static plasma background is used. Therefore, the energy carried by the plasma is constant among all the simulations i.e. \( T_e \) and \( n_e \) are restored after every Monte Carlo cycle. This implies that the increase \( \text{H} \) density is directly due to enhanced recombination of \( \text{H}^+ \). Radial profiles from the model results, taken at 3 cm in front of the target, are shown in Fig. 6.

In such simulations, plasma beam has a FWHM of 20 mm (between \(-0.01 \) and 0.01 m), with \( T_e \) peak at 1.5 eV and \( n_e \) at \( 2.5 \times 10^{20} \text{ m}^{-3} \). Both those parameters have a Gaussian profile. The density of \( \text{H} \) increase from \( \approx 1 \times 10^{19} \text{ m}^{-3} \) to \( \approx 3.5 \times 10^{19} \text{ m}^{-3} \) between the 0% and 20% \( \text{N}_2 \) seeding. The only difference between the 0% \( \text{N}_2 \) case and the ones with \( \text{N}_2 \) is the addition of new reaction paths i.e. N-MAR (reaction 3) and the proton transfer from \( \text{H}_2^+ \) and \( \text{N}_2 \), yielding \( \text{N}_2\text{H}^+ \) and followed by dissociative recombination:

\[
\text{H}_2^+ + \text{N}_2 \rightarrow \text{N}_2\text{H}^+ + \text{H}\text{Proton transfer}
\]

\[
\text{H}_2^+ \rightarrow \text{e}^- + \text{NH} + \text{NDissociative recombination}
\]

\[
\rightarrow \text{N}_2 + \text{HDissociative recombination}
\]

(4)

Reaction 4 is found by numerical simulations be relevant from the edges of the plasma beam outwards, where \( n_e \) goes below \( 5 \times 10^{19} \text{ m}^{-3} \) and the \( \text{H}_2^+ \) sink mechanism producing \( \text{N}_2\text{H}^+ \) is favourable compared to the dissociative recombination (DR) channel, according to the relation:

\[
\frac{d[H_2^+]}{dt} = (k_{IC}[H^+]^2[H_2])_{\text{source}} - (n_e[H_2]^+ k_{IC})_{\text{sink}} - ((N_2[H_2]^+ k_{N-MAR(4)})_{\text{sink}}
\]

With \( k_{IC} \), \( k_{DR} \) and \( k_{N-MAR(4)} \) being the rate coefficients for ion conversion, dissociative recombination of \( \text{H}_2^+ \) and N-MAR(4). Moving radially towards the centre of the beam, electron density increases, hence \( \text{H}_2^+ \) is predominantly lost via DR. These processes, in particular N-MAR (3), seem to further contribute to enhance the recombination efficiency in respect to only-\( \text{H}_2 \) seeding. Such influence is due to the role played by \( \text{NH}_x \) molecules and \( \text{NH} \) radical, being the final product of IC-DR cycles of \( \text{NH}_x \) with \( 1 < x \leq 3 \). To further investigate the role of N-MAR, Eunomia simulations have been carried out with and without N-MAR for the same content of seeded \( \text{N}_2 \). The model and the plasma

Fig. 3. Electron density and temperature radial profiles with different \( \text{N}_2 \) concentrations. Background pressure has been kept constant at 2 Pa (left) and 4 Pa (right).
parameters are identical in both cases. The obtained radial H density profiles are shown in Fig. 7.

The density of H with N-MAR is calculated to be higher by a factor \( \sim 2.5 \), showing the importance of such process on the recombination of \( \text{H}^+ \).

A scan among five different \( \text{N}_2 \) concentrations in a fixed overall background neutral pressure in the target chamber has been carried out while monitoring with OES the peak intensity of \( \text{NH} \) \((\text{A}^3\Sigma^+\rightarrow\text{X}^3\Sigma^- v' = 0 \rightarrow v'' = 0) \) transition band at 336 nm [31], \( \text{NH}_x \) content with RGA and the total static plasma pressure, calculated as 

\[
P_k = \frac{n_e T_e}{2} \frac{\text{e}^2}{\beta}
\]

by means of TS. The intensity of the band at 336 nm has been calculated as 

\[
I_d(t) = \int I(\lambda) d\lambda
\]

integrating the intensity over the width of the line profile. Results are reported in Fig. 8.

The plasma pressure drops by \( \sim 30\% \) in both cases, passing from 0.12 to 0.08 kPa at 4 Pa and from 0.21 kPa to 0.14 at 2 Pa. This is due to the reduction of electron density while increasing the \( \text{N}_2 \) content in the seeded gas mixture. We address such behaviour to be due to nitrogen-included molecular-activated recombination (N-MAR). Simulation results shown in Fig. 6 point to the same conclusion. It is worth underlining that \( T_e \) remains constant among all the different \( \text{N}_2 \) seeding percentages.

The molecular peak intensity of \( \text{NH}_x^* \) (RGA) are similar in both background neutral pressure scenarios, even though the overall content of \( \text{N}_2 \) is higher in the 4 Pa environment. The conversion efficiency (in%) has been calculated by taking the peak values of the RGA signal of the different N-included species and is calculated as follows:

\[
\text{Conversion efficiency} = \frac{\sum_{\text{NH}_x^*} N_{\text{value}}}{\text{NH}_x^*} \times 100,
\]

obtaining 4.5% in the 2 Pa case and 2.8% in the 4 Pa one. Such difference shall explain the values in Figs. 5(b).

5. Helium and nitrogen seeding: a comparative study

A dedicated set of experiments has been carried out with the purpose of highlighting the role molecular-induced processes in an impurity-seeded detachment scenario. \( \text{N}_2 \) and \( \text{He} \) have been seeded separately, together with hydrogen, from 0 to 20% at background neutral pressure corresponding to 2 and 4 Pa. Helium has been chosen in order to exclude molecular-activated processes. Plasma parameters have been diagnosed with TS, while the heat flux to the W target have been monitored by means of calorimetry and calculated as follows:

\[
P(W) = \text{flow} \times \frac{\Delta T}{\text{water}} \times \frac{\text{mass flow}}{\text{heat capacity}}
\]

The power is then divided by the surface area. The mass flow is equal to 0.4 kg/s, \( \Delta T \) is the temperature difference (in K) of the water before and after the heating occurring when flowing through the heated target and 4200 \( \text{J/kg K} \) is the specific heat of water. The experimental parameters are the same as in Section 4.

When He is injected into the system, no significant variation on the plasma pressure is present in the 2 Pa case, while a net increase of almost 20% is measured in the 4 Pa one. This is in net contrast to what we observed in Fig. 8a, which is characterised by a clear drop while increasing the content of \( \text{N}_2 \) in the puffed mixture. If in the nitrogen-seeding case, detachment is enhanced by increasing the \( \text{N}_2 \) ratio, in the He one we observe an opposite trend. To provide further insights, calorimetry measurements have been carried out and the derived incoming heat flux to the target is plotted in Fig. 9.

The heat load onto the W target is due to ion recombination at the wall, releasing their potential hence causing heating on the material. The power deposited on the surface with only \( \text{H}_2 \) seeding is 1.33 MW/m\(^2\) and 0.74 MW/m\(^2\) at background pressures of 2 and 4 Pa. In the \( \text{N}_2 \)
puffing cases, a net decreasing in the heat load occurs, leading to -1.2 MW/m² at 2 Pa and 0.63 MW/m² at 4 Pa. The observed behavior seems to be due to the active role of N-MAR, where NHₓ molecules act as electron donor in the ion conversion with H⁺, contributing to the overall heat flux reduction of 12% at 2 Pa and 18% at 4 Pa.

This increased recombination is qualitatively in line with numerical simulations. When looking at the He case, we observe again a reversed behavior. In fact, the power loads on the target increase linearly with enhancing the amount of He in the injected gas mixture, leading to heat loads raised by 10 and 16% for 2 and 4 Pa. In this case, we exclude a priori any further molecule-induced plasma chemical processes, being N₂ substituted with a poorly-reactive atom i.e. He. It seems clear that the dilution of hydrogen molecules with He implies a lower occurrence of recombination reactions, hence more ions are eventually reaching the target plate. In the N₂ case we see two recombination mechanisms occurring simultaneously i.e. N-MAR and MAR.

The opposite trends between H₂/N₂ and H₂/He seeding observed in both plasma pressure and heat loads, are indications that (i) nitrogen leads to enhanced recombination, (ii) He in the mixture decreases the ion conversion by diluting H₂. This holds for both scenarios examined i.e. at background neutral pressure in the target chamber of 2 and 4 Pa.

N-MAR appears to actively contribute to enhance the recombination of hydrogen ions in the vicinity of the target in a detached-like scenario. This is the first time that this catalytic effect led by N—H molecules is observed in ITER-relevant plasma-surface interaction environment.

6. Summary and conclusion

Plasma detachment experiments with impurity seeding have been carried out in linear machine Magnum-PSI, aiming to confirm experimentally the role of N₂ and N—H species in enhancing the recombination of H⁺ in ITER-relevant divertor detached-plasmas. Firstly, two cases of study have been set up i.e. by seeding neutral gas in the target chamber up to 2 and 4 Pa. Per case, a scan among H₂/N₂ ratio with nitrogen from 0 to 20% has been done. By increasing the content of N₂ in the puffed mixture, a ~30% reduction of the plasma pressure is observed in both cases. OES and RGA measurements show a linear increase of NHₓ species as a function of N₂ content. In order to investigate the role of N-induced plasma chemistry in a detached hydrogen plasma, the same experiment has been pursued i.e. seeding separately H₂/N₂ and H₂/He mixtures in identical experimental conditions. In such way, nitrogen-molecular-assisted processes are excluded beforehand in the Helium case. The plasma pressure again decreases in the case of nitrogen, while it increases with He. Calorimetry measurements show the same trend, with heat flux decreasing with N₂, and increasing with He. We attribute such observations to be due to N-MAR. This two-step process is initiated by ion conversion, then followed by dissociative recombination i.e. effectively converting ions to neutrals. Numerical simulations point qualitatively to the same conclusion. A quantitative comparison between these experimental results with a couple code (fluid and kinetic) is currently under preparation and will provide more detailed insights in the most relevant processes causing the observed experimental results.
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Supplementary materials

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