EFDA–JET–CP(12)02/42

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First Nitrogen-Seeding Experiments in JET with the ITER-Like Wall

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in Proceedings of the
20th International Conference on Plasma Surface Interactions , Eurogress, Aachen, Germany
21st May 2012 - 25th May 2012

ABSTRACT

In this contribution we present results from the first N_2 seeding experiments in JET performed after installation of the ITER-like Wall. Gas balance measurements for seeded L-mode discharges indicate very strong N_2 retention as well as a potential increase in D_2 retention. The possible influence of ammonia production on this apparent retention is discussed. Plasma parameters and impurity content were monitored throughout the seeded discharges as well as during subsequent clean-up discharges. These experiments give first insight into phenomena related to the use of nitrogen as seeding gas in JET with the ITER-like Wall, such as ammonia production and nitrogen legacy.

1. INTRODUCTION

The reduction of power loads on the tungsten divertor target of ITER is mandatory in relevant heated scenarios. To this aim it is foreseen to seed noble gases or nitrogen into the divertor plasma. The seeding species will interact with the plasma-facing materials beryllium and tungsten. In the case of nitrogen also chemical reactions with the wall surfaces as well as with hydrogen have to be considered. The efficiency as well as the side effects of N_2 seeding in a tokamak with a first wall that consists of Be and W are currently being studied at JET with its ITER-Like Wall (ILW) (1; 2). In this paper we present results from the first experiment with N_2 injection in JET-ILW. The main aim of this experiment was to assess the nitrogen retention and the influence of N_2 injection on the retention of hydrogen isotopes. Furthermore, the impurity content in the vessel was monitored at various N_2 injection levels as well as during subsequent clean-up discharges.

2. GAS BALANCE

The chosen scenario for the gas balance with N_2 seeding was a standard L-mode with low triangularity, ohmic heating, 2.0MA plasma current and 2.2T toroidal field. N_2 was injected into the divertor scrape-off layer through the toroidally symmetric gas injection ring (GIM9) close to the horizontal W target plate on which the outer strike-point was positioned. The core density in the flat top phase was 2.5×10^{19} m^{-3} in the first discharges. It was lowered in later discharges to 1.8×10^{19} m^{-3} to be able to inject more N_2 without running into a radiation limit. The plasma-facing surfaces were loaded with nitrogen by steadily increasing the N_2 injection with each discharge. Injection rates between 1.4 and 5.4×10^{21} electrons per second and ratios of N_2 to D_2 (in molecules per second) from 0.04 to 1.3 were covered. Before the experiment, a LHe cryo regeneration was performed in order to collect only the gas consumed in this experiment. After 13 successful discharges the liquid helium (LHe) cryo panel of the pumped divertor was regenerated again. The released gas was transferred to the Active Gas Handling System (AGHS) where its total volume and composition was measured. Subsequent to this loading session, a series of clean-up discharges without N_2 injection was performed with the aim to remove nitrogen stored in the plasma-facing surfaces. These included limiter discharges with scans of the radial gaps, divertor discharges with large strike-point sweeps as well as divertor discharges with additional 2MW of ion cyclotron heating. After 18 clean-up discharges the LHe cryo panel was regenerated once more and the gas analyzed in the AGHS.

The results of the two gas balances are shown in Table 1. The most striking evidence is that about half of the injected N_2 was not recovered in the AGHS upon the first regeneration of the LHe cryo panel. This is in accordance with the strong gas consumption observed with the CFC-wall after heavy Be evaporation (3). The percentage numbers for the apparent retention of D and total amount of gas have to be compared to non-seeded L-mode discharges at a similar density. In the ILW-configuration the total retention (corresponding roughly to the D_2 retention) is typically around 1-2% in similar discharges, corresponding to retention rates of about 5×10^{19} D/s normalised to the divertor phase (4). Thus, the apparent overall retention is considerably increased by the N_2 injection. In the extensive series of non-seeded cleaning discharges only 6 mbar·l of N_2 were injected in a short blib (for determination of the pumping speed), while 11 times more was recovered upon regeneration of the LHe cryo panel. However, this amounts to merely 16% of the N_2 that was missing after the first regeneration.

Laboratory experiments have shown that the amount of nitrogen retained upon implantation into Be or W saturates very quickly (5; 6). The surface layer thickness within which nitrogen is retained corresponds to the range of the energetic N particles in the solid and is therefore limited to a few nm. In this thin layer nitrogen atomic fractions up to 0.5 are reached, consistent with the formation of a surface layer of nitride (Be_3N_2 and WN). No diffusion of N into the bulk of the metals was observed. This allows a simple estimation of the amount of N that can be stored as nitride after implantation into plasma-facing materials. To first order, the contribution of the W surfaces in the divertor is neglected due to their smaller area and the shallower penetration depth of energetic N atoms in the high-Z material. Assuming a Be surface area of 200m^2 and a penetration depth of 10nm (corresponding to an implantation energy of a few keV) leads to 1.2 bar·l of N_2 that can be stored as beryllium nitride on plasma-facing surfaces. This compound is very stable (with a higher melting temperature than metallic Be (7)) and can efficiently store the implanted nitrogen.

While this estimation indicates the order of magnitude, it is a strong simplification. Saturation of a surface layer with nitrogen might occur only on the surfaces exposed to the highest ion fluxes, i.e. the limiters. This leads to a much reduced relevant Be area. Furthermore, the simultaneous bombardment of these surfaces with energetic D leads to sputter-erosion of the nitride layer, thereby further reducing the amount of retained nitrogen. Therefore, 1.2 bar·l is rather an upper estimate of the net amount of N_2 that can be stored in plasma-facing surfaces in JET. On the other hand, significant amounts of nitrogen can also be stored in co-deposits. Typical N/Be ratios in the range of 0.1-0.2 were observed in co-deposits produced in the PISCES B laboratory (8). Co-deposition with carbon can be neglected: The amount of C in the ILW-vessel is reduced by an order of magnitude with respect to JET-CFC (9). In accordance with this finding, no CN molecules were observed by spectroscopy.

A similar estimation for experiments performed at ASDEX Upgrade has lead to the conclusion that the assumed area of its W surfaces is not large enough to explain the observed N retention (10).

An increased effective surface area due to rough surfaces was proposed as a possible reason for the observed discrepancy. However, more recent investigations on the composition of the pumped gas in N_2-seeded and subsequent discharges have revealed a strong influence of ammonia formation on the gas balance (11). It is known that metal surfaces can act as efficient catalysts for the formation of ammonia from hydrogen and nitrogen (12). In the here presented experiments any ammonia produced will not appear in the gas balance since at liquid nitrogen temperatures it has a vapor pressure of 10-11 mbar. It is, therefore, pumped by the liquid nitrogen cryo panel and cannot be recovered upon regeneration of only the LHe panel. Ammonia production, therefore, needs to be considered a possibly important contribution to the observed N retention also in JET.

Form the gas balance results in table 1 the maximum amount of ND_3 produced in the N2-seeded discharges can be estimated. This amount is limited by the missing D_2 to 0.5 bar·l. This means that a maximum of 1/3 of the injected N atoms can have been converted to ammonia. For a more conservative estimate it can be assumed that the ‘normal’ D_2 retention mechanisms, that in similar non-seeded discharges lead to a D_2 retention of up to 2%, are not affected by the N2 injection. The observed increase in D_2 retention by 1.7% (0.3 bar·l) would still correspond to the formation of 0.2 bar·l of ammonia (1/7 of the injected N atoms converted to ND3). This amount is still considerable and would have implications on the design of the ITER tritium plant.

3. INDICATIONS OF AMMONIA PRODUCTION

3.1. VISIBLE SPECTROSCOPY

The mirror-link spectroscopy system was used to record line radiation emitted by the plasma in the visible wavelength range during N_2-seeded discharges. It can detect emissions from ND radicals, which feature a distinct band emission at 336.0nm. The formation of these molecules is a sign of ongoing plasma chemical reactions and would be an indication also for ND_3 production. The lines-of-sight of the mirror-link spectrometer cover the whole horizontal W target. Figure 1 shows a clear signal peak at 336.0nm during N_2 seeding.

In Figure 2 the integrated intensity of this signal is color-coded and plotted as a function of time and position along the horizontal target. The position of the outer strike-point is indicated. The signal from ND molecules is localized around the projection of the strike-point. Its temporal evolution is strongly correlated to that of the NII intensity at 500.5nm.

3.2. RESIDUAL GAS ANALYSIS

While visual spectroscopy indicates the formation of ND molecules, which in turn suggests the production also of ND_3, it has proven challenging to confirm this with in-situ mass spectrometry. Time resolved signals at several mass-to-charge ratios including 28 (N_2) as well as 18 (ND_2), 19 (ND_2H), and 20 (ND_3) were recorded in the pump duct below the outer divertor. Shot-integrated partial pressures were derived by integrating the background-subtracted signals over the duration of each discharge. There is a clear correlation between the partial pressure at the m/e ratio of 28 and the injected amounts of N_2. With a known pumping speed (measured for N_2 without plasma) this can be converted into gas consumption, which is plotted in the top graph of Figure 3 as a function of the integral amount of N_2 injected in the discharge. A linear fit to the calculated N_2 consumption yields a value of 0.46 in reasonable agreement with the overall amount of N_2 missing in the loading session (see Table 1). The bottom graph shows the shot-integrated partial pressures for mass to charge ratios indicative of (deuterated) ammonia. Here no correlation is observed. This seems to contradict the strong ammonia production that is indicated by the global gas balance and the spectroscopy measurements. This discrepancy might be due to contributions to the mass spectrometer signals from (deuterated species of) water and/or methane (11).

4. NITROGEN LEGACY

The legacy of nitrogen in the vacuum vessel after N_2-seeded discharges used to be an operational difficulty in JET with the carbon wall (3). With the new ITER-like Wall this issue is less compromising: The N impurity levels and plasma parameters in subsequent N_2-seeded L-mode discharges depend dominantly on the N_2 injection rate in the discharge itself or, more precisely (because a steady state is not reached in these discharges), on the amount of N_2 injected up to the measurement point. This is exemplified for the core radiation in Figure 4.

While no obvious legacy is observed in the seeded phase of the discharges, clear signs of nitrogen legacy were monitored in the non-seeded reference phase at the beginning of each discharge. Figure 5 shows the shot-to-shot evolution of the NII line intensity at 500.5nm at the position of the outer strike-point in the non-seeded reference phase. The nitrogen recycling flux around the outer strike-point increases with increasing amount of N_2 injected in the foregoing discharge and drops again steadily in the non-seeded discharges.

CONCLUSIONS

Nitrogen-seeded L-mode discharges were successfully run at JET with the ITER-like Wall. A gas balance resulted in very strong apparent N_2 retention and increased D_2 retention. The influence of production of deuterated ammonia on this gas balance could not be quantified and dedicated experiments for further investigations are planned. A clear nitrogen legacy is observed spectroscopically in a non-seeded reference phase of the discharges. The legacy strongly decays from shot to shot in non-seeded discharges. The impurity content and plasma parameters in the seeding phase of each discharge are not influenced by the amount of N_2 injected in preceding discharges. This relaxes an operational difficulty previously encountered with the carbon wall.

ACKNOWLEDGEMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Loading	Injected	Missing	Removal	Injected	Missing
N_2	0.77 bar·l	52.5%	N_2	6 mbar·l	−66 mbar·l
$D_2 + H_2$	19.61 bar·l	3.7%	$D_2 + H_2$	21.64 bar·l	1.4%
Total	20.38 bar·l	5.5%	Total	21.65 bar·l	1.1%

Table 1: Results of the two gas balances performed after the series of N2-seeded discharges and after the subsequent cleaning discharges.

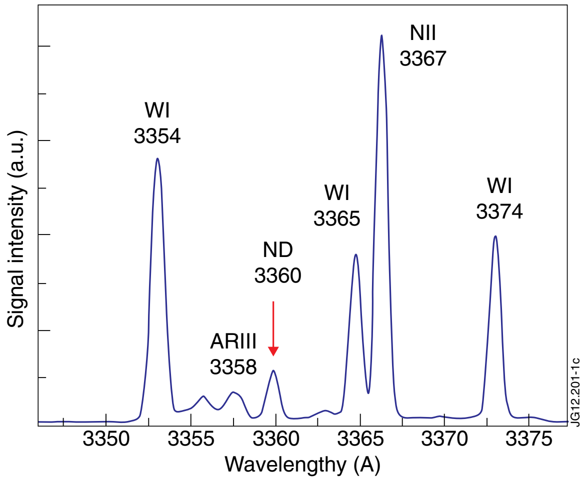

Figure 1: Line radiation from ND molecules observed along a line of sight looking at the outer strike point.

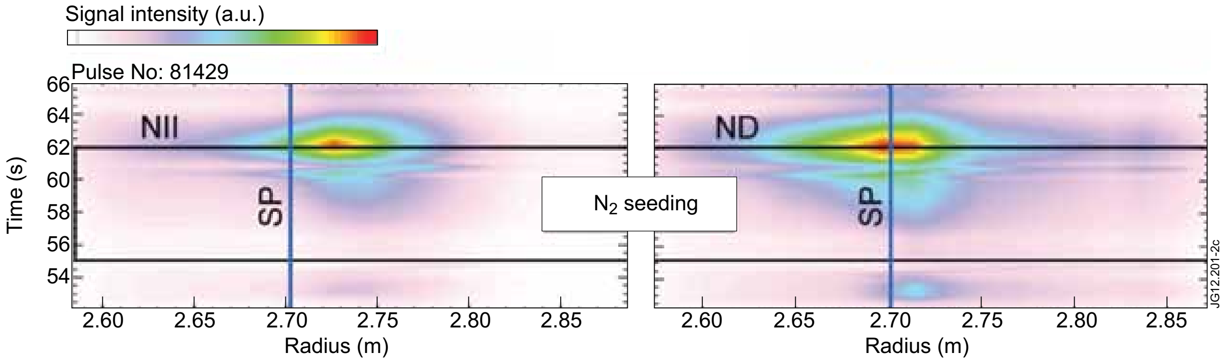

Figure 2: Contour plots of ND and NII signals versus time and position along the horizontal target.

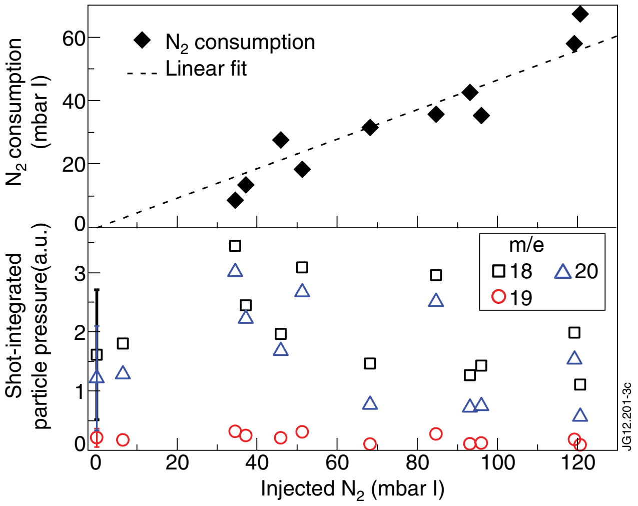

Figure 3: Top: Shot-integrated N_2 consumption (injected minus pumped) for all N_2 seeded discharges as a function of total amount of N_2 injected within the discharge. Bottom: Shot-integrated partial pressures for the mass-to-charge ratios that could be a signature for (deuterated) ammonia.

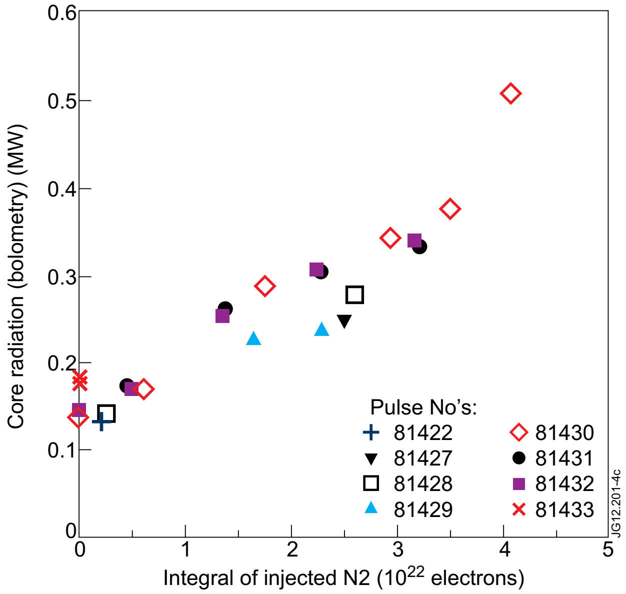

Figure 4: Core radiation from bolometric measurements during the N_2-seeding phase of various discharges as a function N_2 injected up to the point of measurement.

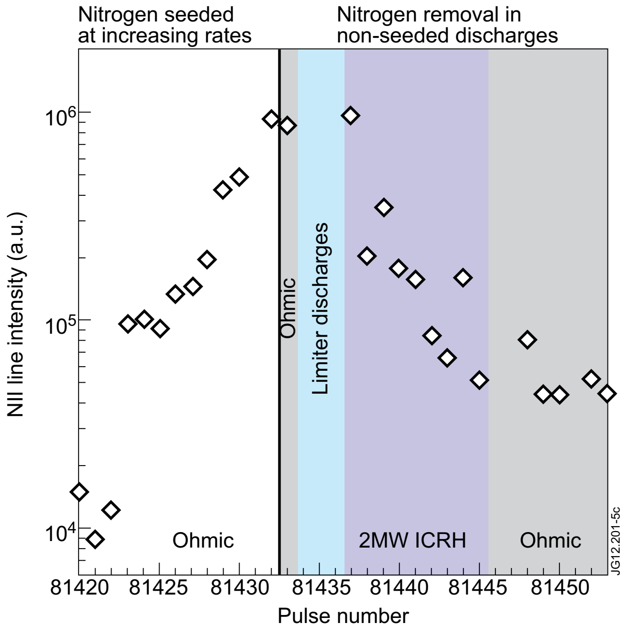

Figure 5: Evolution of the NII line radiation at 500.5nm from shot to shot. The logarithm of the line intensity along a line of sight looking onto the outer divertor target close to the outer strike-point was averaged over a time window with no N_2 injection at the beginning of each discharge.