*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, O-2.004 (2009)*

# Confinement enhancement in ASDEX Upgrade improved H-mode discharges with nitrogen seeding

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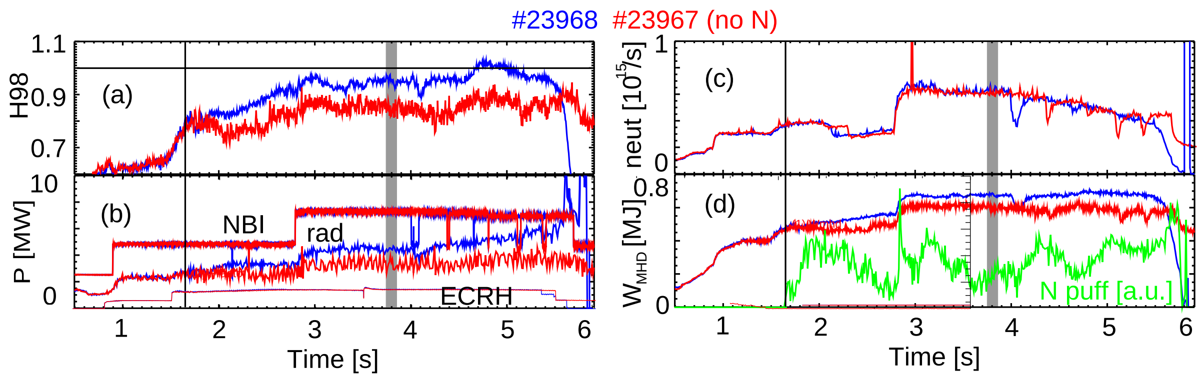
## 1 Introduction

Tungsten has been studied for 10 years on ASDEX Upgrade as a possible first wall material for fusion reactors [1]. The feasibility and the performance of the advanced scenarios are assessed, in order to deal with the technological challenges of a burning plasma. In particular hybrid scenarios, such as ASDEX Upgrade's improved H-mode discharges, require high heating power, a challenge to the tolerable heat flux on the divertor plates. A significant tungsten in-flow from the first wall would lead to performance degradation and, in case of accumulation, to a radiative collapse. A method to control the power load to the divertor is to induce radiative plasma cooling. In this work we analyse the core transport in ASDEX Upgrade improved H-mode discharges with nitrogen seeding [2].

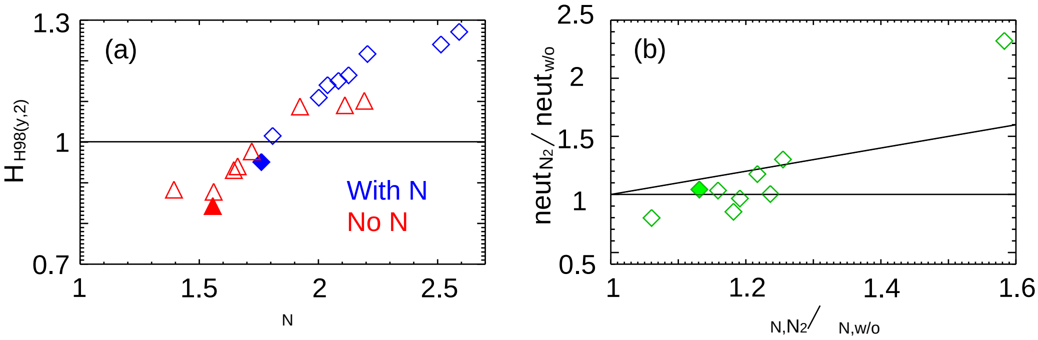
## 2 Nitrogen seeding and confinement

In Fig. 1 the time traces of discharges #23967 (no $N_2$ puffing, in red) and #23968 (with $N_2$, in blue) are shown. The pair is chosen for the good signals of the relevant core diagnostics and for having identical machine conditions. Although the $H_{H98(y,2)}$ factor is the lowest in our database (see Fig. 2 (a)), its enhancement by 10-15% due to $N_2$ is representative of the typical improvement observed. The radiation is indeed higher in the




**F**igure 1. Time traces of the discharges #23968 (blue), with $N_2$ seeding, and #23967 (red), without. (a) $H_{H98(y,2)}$, (b) NBI, ECH and radiated power, (c) neutron rate, (d) stored energy and $N_2$ puff rate. The vertical line labels the beginning of the $N_2$ puff. The shaded region is the time interval used for the analysis.

discharge with nitrogen seeding (#23968, blue trace in Fig. 1 (b)), therefore the radiative cooling is effective. The nitrogen discharge has a better energy confinement, resulting in a 10-15% higher $H_{H98(y,2)}$ (Fig. 1 (a)) and in more total stored energy, plotted in (d), the input power being the same in both discharges. Nevertheless, the neutron rate is the same (c). In general we observe a systematic enhancement of both $H_{H98(y,2)}$ and $\beta_N$ by 10-25% for all discharges with nitrogen seeding, as summarised in Fig. 2. The neutron




**F**igure 2. Full symbols refer to the pair of discharges #23967 and #23968 around 3.8 s. (a) $H_{H98(y,2)}$ as a function of $\beta_N$. (b) Ratio of the neutron rate for pairs of discharges with and without $N_2$ seeding, versus the ratio of $\beta_N$. The lines y=1 and y=x are overplotted.

rate, instead, either does not increase with nitrogen seeding or it increases less than $\beta_N$ (see Fig. 2 (b)), although it should increase more than linearly with the stored energy [3]. This discrepancy can be explained by a different impurity concentration, which reduces the deuterium density $n_D$ for a given electron density $n_e$. Since $Z_N = 7$, a nitrogen concentration $c_N = 1\%$ corresponds to a $\Delta n_D$ = -7% and to a $\Delta Z_{eff} = 0.42$. The neutron rate scales roughly linearly with $n_D$ in case of beam-target neutrons, quadratically in case of thermonuclear reactions [4]. MonteCarlo simulations with the TRANSP code [5] predict dominant beam-target reactions and a drop of 20% in the neutron rate for $c_N = 3\%$ (not shown here).

## 3 Transport analysis with and without nitrogen seeding

It is important to determine the plasma region where the confinement improvement occurs. Indeed, it is not obvious why the energy confinement should improve with a higher impurity content in the plasma, as the impurities cool the plasma via radiation. Therefore it is of relevance to identify the channel where the confinement improves, in particular whether it is the density or the temperature profiles - at this high collisionality, ion and electron temperatures are close to each other. The electron and ion temperature profiles at 3.8 s are shown in Fig. 3, measured with Electron Cyclotron Emission and Charge eXchange Recombination Spectroscopy (CXRS), respectively. Both the ion and the electron temperature profiles are higher by about 10% in the case with nitrogen, at least for $0.3 < \rho_{pol} < 0.8$, the so-called confinement region. This is observed robustly also at subsequent time frames. In both Fig. 2 (a) and (b) it appears that, although a slightly higher pedestal temperature is not ruled out, there is clearly a higher temperature gradient just outside half radius in the case with nitrogen. The density profile, instead, displayed in Fig. 4 (a), is unaffected by the nitrogen seeding. In particular, the profile of #23968 (blue) is flat, like for #23967 (red), as long as the Electron Cyclotron Heating (ECH)

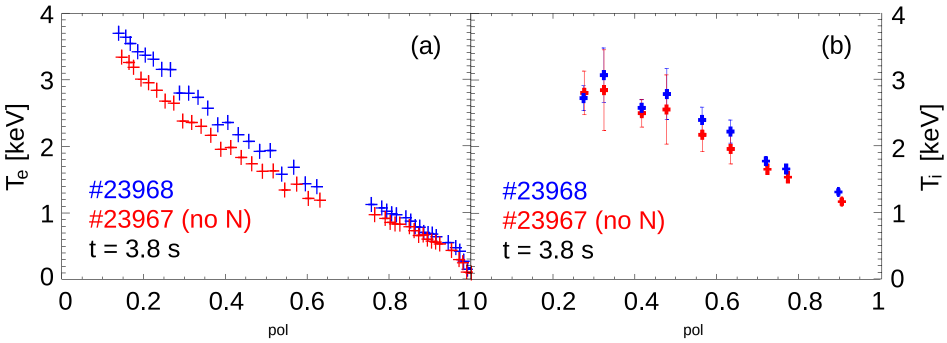



**Figure 3.** (a) $T_e$ and (b) $T_i$ profiles. Colours like in Fig. 1.

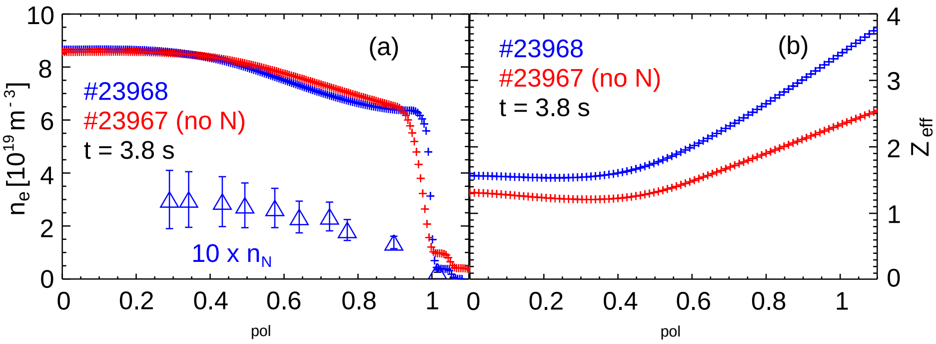



**Figure 4.** (a) $n_e$ and $n_N$ (x10) and(b) $Z_{eff}$ profiles. Colours like in Fig. 1.

power is sufficient to provide the necessary pump-out. Afterwards, accumulation leads to a radiative collapse. The confinement improvement is not due to stronger density peaking; in general at high collisionalities the density profiles are observed to be flat in ASDEX Upgrade H-modes [4]. The difference of the energy content between the two discharges, which amounts to 10%, is due to the temperature increase, at least in this pair of discharges.

Overplotted in Fig. 4 (a) is the nitrogen density profile for #23968, measured with CXRS and multiplied by a factor 10. The profile is flat within the experimental uncertainty. The nitrogen concentration is as high as 3%, leading to $\Delta n_D \approx$ -20% and $\Delta Z_{eff} \approx$ 1.2, assuming the other impurities to be present in the same amount in both discharges. This is higher than the difference between the $Z_{eff}$ profiles in Fig. 4 (b), varying from 0.2 in the center up to 1 at the separatrix. The measured $c_N$ is high enough to dilute significantly the deuterium. Dilution is known to have a stabilising effect on the Ion Temperature Gradient (ITG) driven mode, as for the Radiative Improved mode [6] and for ASDEX Upgrade ion internal transport barriers [7]. In order to assess the dilution effect quantitatively, we performed a gyrokinetic scan of $c_N$ with the code GS2 [8] under the experimental conditions. The scan confirms that the dominant mode is an ITG, as expected at this medium-high collisionality [5]. Dilution has a significant effect, reducing the growth rate in Fig. 5 (a). A stability analysis of the mode as a function of its main drive, i.e. $R/L_{T_i}$, is performed for different $c_N$ levels at half radius. The result in Fig. 5 (b) is a shift of the the gradient length by 15% for $c_N = 3\%$. This is consistent with the

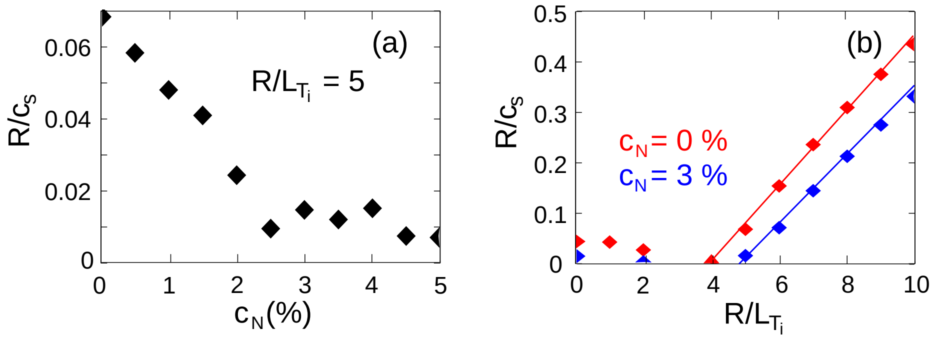



**Figure 5.** ITG stability analysis at half radius. (a) Growth rate as a function of $c_N$. (b) Grwoth rate versus $R/L_{T_i}$ assuming $c_N = 3\%$ (blue) or no $N_2$ (red).

observed enhancement of the energy confinement and with the experimental increase of $\nabla T_i$ and $\nabla T_e$ in Fig. 3.

## 4 Conclusions and outlook

Nitrogen seeding, used for radiative cooling in order to control the power load to the divertor plates in future devices, turns out to improve the energy confinement in ASDEX Upgrade improved H-modes at medium-high density. In particular, a reduction in core heat transport is observed. Impurity peaking is avoided with ECH. Despite the higher stored energy of the nitrogen discharges, the neutron rate does not increase, or it does to a lesser extent. This discrepancy is due to a higher the impurity content, diluting the deuterium and reducing the fusion reactions.

The deuterium dilution is found to play an important role also for the transport reduction in the core plasma. Linear gyrokinetic simulations show a 15% increase in $R/L_{T_i}$ for $c_n$ = 3%, consistent with the experimental $\nabla T_i$ and $\nabla T_e$.

Experiments with pairs of discharges in an unboronised machine are on-going. Preliminary results confirm the improvement of the energy confinement observed after a boronoisation. Further analysis is necessary to compare the kinetic profiles in the pedestal region. A detailed power balance analysis and simulations by means of fluid models could add further evidence to the dilution mechanism found in this paper.

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