The role of carbon on the H-mode confinement in ASDEX Upgrade with a metal wall

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Section 1: Introduction

Future fusion devices such as ITER and DEMO will have metal plasma facing wall components. This is because the conventional use of carbon as a first wall material is prohibited due to its high tritium retention properties. Seeding light impurities (like N_2) is needed to protect plasma facing components from steady state heat loads. An unexpected beneficial effect of this recipe is an improvement of confinement stemming from the pedestal region and resulting in confinement quality previously observed often only in carbon devices [1, 2, 3]. This observation raises the question as to whether nitrogen seeding in metal devices substitutes the presence of carbon as an intrinsic impurity, and which physics mechanisms are at play in the confinement improvement.

Section 2: Experiment.

In AUG the most extensive N_2 seeding studies aiming at confinement optimisation have been conducted in plasmas with a plasma current of I_p = 1MA, B_T =2.5T at low triangularity (δ=0.2) and an edge safety factor of q_{95} = 4.6 [1, 4]. In this paper, this reference scenario has been selected for comparing the effect of N_2 and CD_4 seeding on plasma confinement as part of an ongoing wider study [5,6,7] in which the potential of various seeding gases (He, N_2, CD_4, Ne, Ar and Kr) to optimise the confinement in combination with reduced divertor heat load mitigation, is reviewed.

A control experiment comparing N_2 and CD_4 seeding has been conducted with:

1) a reference plasma without seeding – (#30513) – Γ_D~ 2.5*10^{22} elec/s,
2) a plasma with N_2 seeding – (#30507) – Γ_D~ 2.5*10^{22} and Γ_N ~ 1*10^{22} elec/s,
3) a plasma with CD_4 seeding – (#30518) – Γ_D~1.3*10^{22} and Γ_{CD4}~1.5*10^{22} elec/s.

Halfway through the pulse the upper triangularity is varied from δ_{up}~0.05 to δ_{up}~0.3 (lower triangularity fixed at δ_{low}~0.45). Plasma I_p/B_T = 1MA/2.5T, input power P_{tot}~13MW (P_{NBI}=10MW and P_{ECRH}=1.5MW, P_{Ohm}=0.5MW)

Figure 1 shows that the plasma stored energy W_{MHD}, and normalised confinement $H_{98,y2}$ increase by 20-30%, for both N_2 and CD_4 seeded plasmas (numbering 1-3 as above). The plasma density remains unaffected by the seeding gases and is only affected by the change in plasma shaping where the density normalised to the Greenwald density increases from f_{GW} ~ 0.6 to 0.75. The neutral particle density in the divertor $n_{0\text{-divertor}}$ and main chamber $n_{n\text{-main}}$ remain largely unaffected as does the divertor compression ratio $n_{0\text{-divertor}}/n_{0\text{-main}}$ ~200-230, a typical range for AUG. The confinement benefit of seeding is due to an increase in pedestal temperature by 20-30%, Figure 2&3, while the pedestal density remains unchanged.

*See http://www.euro-fusionscipub.org/mst1.

It should be noted that none of the shots discussed here suffers from confinement degrading 2/1 or 3/2 MHD activity in the plasma centre

The seeding experiment has led to the same impurity concentration, Figure 4, as measured with core and edge charge exchange system: c_{N7+} and c_{C6+} ~1.5-2% going from the plasma centre, and due to the similar charge of C^{6+} and N^{7+} , also similar derived Z_{eff} profiles. The plasma radiation is affected by the introduction of the light-impurity gases. Figure 5 shows the tomographic reconstruction of the AUG bolometric data; as both N and C have their peak in radiation below T=100eV, mainly the divertor radiation is affected. The local radiation pattern of N and C are indeed very similar, with the increase in divertor radiation being the most apparent. The outer divertor remains in an attached regime and moves into a state of high recycling. This is seen from inter-ELM (50-90% of ELM cycle) Langmuir probe measurements (Figure 6) which show a strong increase in the ion saturation current and a slight decrease of the electron temperature for both seeding gases, typical for a transition to a high recycling regime. Note that this experiment does not aim at maximising radiation and detachment like in [6,7].

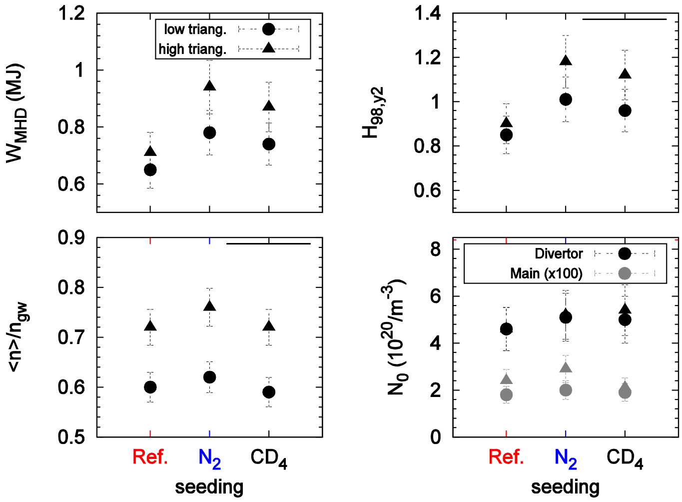

Figure 1: Time averaged parameters for low triangularity phase (t=3-3.2s) and high triangularity phase (t=5-5.2s) for a) plasma stored energy; b) normalised confinement $H_{98,y2}$; c) Greenwald density fraction; d) divertor and outer-mid-plane main chamber neutral pressure

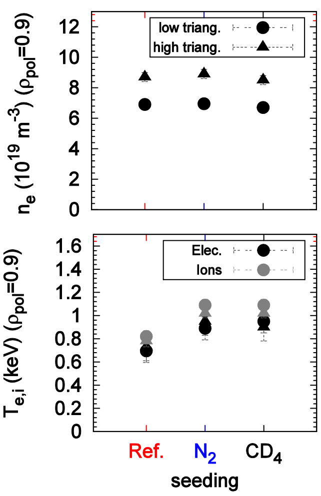

Figure 2: Pedestal density and electron/ion temperature at ρ_{pol}=0.9 for low and high triangularity plasmas

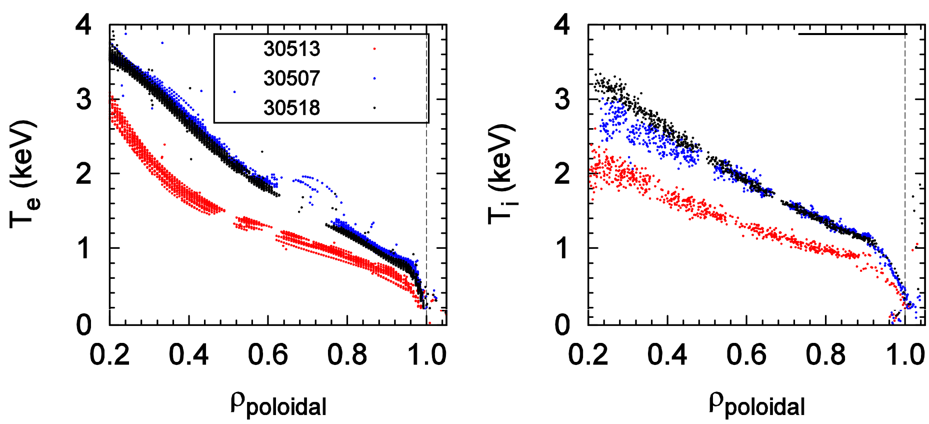

Figure 3: a)T_e from ECE b) T_i from Charge exchange system for low triangularity phase

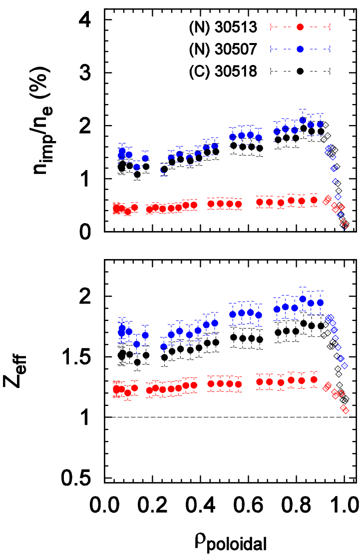

Figure 4: impurity concentration of N^{7+}/C^{6} and derived Z_{eff} for the low δ phase (t=3-3.2s)

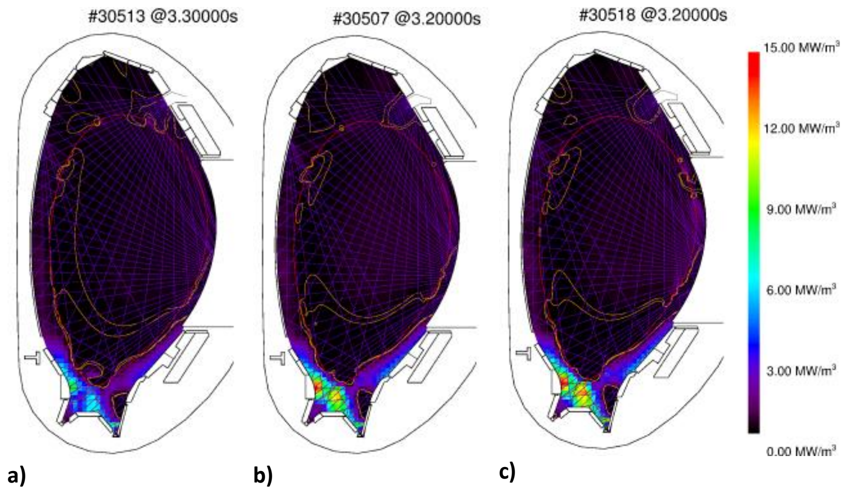

Figure 5a) Reference, b) N_2 seeding c) CD_4 seeding: Radiated power density from tomographic reconstructions of bolometer lines of sight for the low triangularity phases. (high triangularity phases are not shown here, but show similar results)

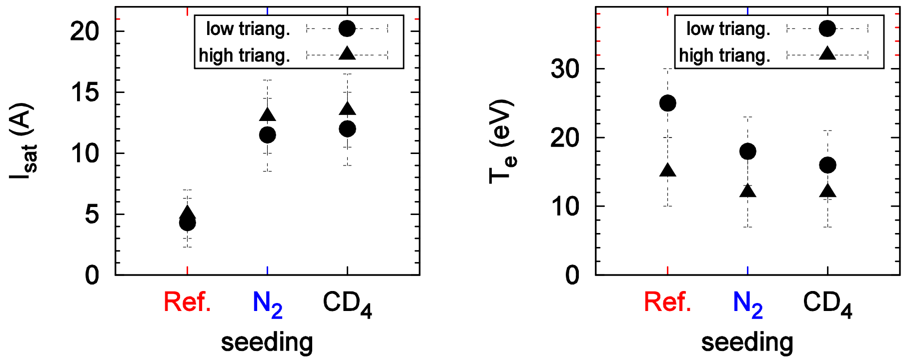

Figure 6a) ion saturation current and b) target temperature as measured by Langmuir probes in between ELMs (50-90% of ELM cycle)

Section 3: Discussion and conclusions

It is observed that seeding either nitrogen or carbon leads to a similar increase of the pedestal temperature by ~20-30%. In other aspects the plasmas look very similar too;

a) the radiation intensity and location are similar
b) the effect on divertor detachment state is similar
c) and the ELMs collapse time is reduced by equal amounts (not shown)

The experiment therefore shows that in a metal wall device, where the presence of carbon is disallowed due to tritium retention issues, nitrogen can be used to replace it as a radiator. Moreover it shows that the lower confinement often found in metal devices compared to carbon devices can (at least partly) be recovered by extrinsic nitrogen seeding. The outstanding question remains: What causes this confinement benefit driven by the pedestal temperature increase?

Ion dilution: The confinement benefit cannot stem from a dilution effect in combination with a hollow Z_{eff} profile. Although figure 4 indeed shows that the Z_{eff} profile is hollow, this is insufficient to cause an 20-30% confinement increase, as quantified in [3].
Core transport: The core profiles are stiff, like in [1, 3] so the confinement benefit cannot be caused by reduced core transport.
Reduced particle exhaust: both carbon and nitrogen are ‘sticking’ impurities [8], and could therefore influence the outgassing of deuterium from the first wall. However no evidence of a reduced neutral particle pressure is observed.
Pedestal stability: The seeded and unseeded pedestals are consistent with peeling-ballooning pedestal stability [5]. This as such does not explain why a higher pedestal temperature is obtained. The seeded plasmas have a higher β_N than the unseeded one, which allows for reaching the ballooning limit at elevated pressure gradient. However, this does not explain the dynamics how the plasma reaches the increased β_N in the first place
Another related possibility is that the impurity seeding affects the ratio of pressure gradient versus bootstrap current [5] in a way that allows a route to larger pressure gradients. This indeed can happen, but pedestal modelling shows that this can only cover a ~5% increase in p_{ped} in a static situation.
Separatrix temperature: Finally, an option is presented where N_2 (or CD_4) seeding cools the separatrix temperature which effectively then shifts the steep pressure gradient region inwards to a region in the magnetic equilibrium where increased pressure gradients can be sustained. Simulations for JET have shown that a reduction of T_{sep} from 100eV to 80eV, combined with a rigid shift of a modelled tangent hyperbolic pedestal profile, can indeed lead to an increase of the pedestal top pressure by 20-30% [9]. This would also require a reduction of the separatrix density, and therefore it is not certain that this is what happens in experiment presented here. The difficulty here is that to proof this mechanism experimentally, the profiles position with respect to the magnetic equilibrium needs to be known well within the current error margin of ~1cm.
In conclusion, the experiment presented here shows that the intrinsic presence of carbon in devices with a carbon plasma facing wall, can (at least in some cases) be replaced by nitrogen in metal devices. The two gases have very similar radiation potential and radiate mostly at temperatures below T_e=100eV, [10,11], which at similar impurity concentrations, leads to similar radiation and detachment behaviour. Some promising mechanisms have thusfar been presented to explain the confinement benefit, but a full understanding remains outstanding.

Ackowledgements
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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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