

Reduction of turbulence and transport in the Alcator C-Mod tokamak by dilution of deuterium ions with nitrogen and neon injection

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Earlier studies on turbulence and transport in ohmically heated C-Mod plasmas indicated that to get agreement between gyrokinetic code predictions and measured values of the ion thermal diffusivity, the main ion species deuterium charge density had to be reduced relative to that of electrons by 10-30 %, implying the presence of a few percent of intrinsic impurities with an effective ion charge of 8-10, corresponding to Oxygen like impurities [1]. Gyrokinetic code modeling of these results with TGLF [2] and GYRO [3] showed good agreement of reduced ion transport and reduced levels of turbulence but only if the dilution of deuterium charge density was introduced in the code, roughly in agreement with experiments (see Fig. 1, reproduced from Ref. [1]).

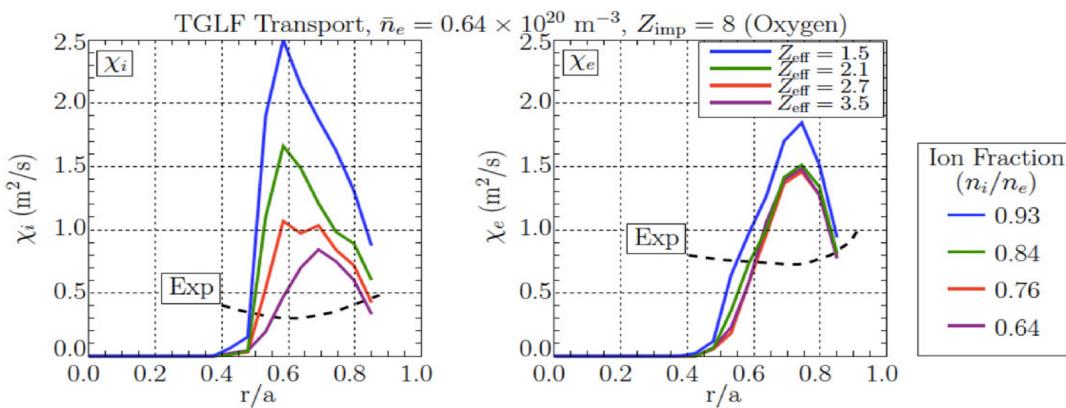


Fig. 1. Ion and electron thermal diffusivities χ in Alcator C-mod ohmic plasmas as predicted by TGLF. The experimental levels are indicated by the dashed line. $B_T = 5.2 \text{ T}$, $I_p = 800 \text{ kA}$, $q_{95} = 3.2$.

Additional transport due to the impurity species in the code was found to be negligible at the experimentally relevant impurity fractions as compared with the overall ion transport dominated by the main deuterium species. More recently, additional experiments were carried out in C-Mod where in relatively clean discharges known amounts of nitrogen were injected into the plasma so that dilution of the deuterium

species was comparable to the earlier intrinsically diluted plasmas [4]. The measurements and simulations showed consistently that the dilution from the nitrogen seeding reduced turbulence and associated energy transport in the radial range of $0.7 < r/a < 0.9$ where strong ITG turbulence dominated transport, well above gyro-Bohm levels.

Measured turbulence levels with phase contrast imaging agreed with the gyrokinetic code predictions based on synthetic diagnostic method [4, 5]. In the code studies it was verified that dilution itself, rather than Z_{eff} was responsible for the stabilizing effect on turbulence. In the linear ohmic confinement regime (LOC) the physics behind turbulence reduction was the result of an increase in the critical temperature gradients, while in the saturated ohmic confinement regime (SOC) a reduction in the ion temperature stiffness was the fundamental cause of turbulence and ion transport reduction. Interestingly, the electron thermal diffusivity was not greatly affected by ion dilution. Thus, it is the improved stability of ITG modes that was mainly responsible for the transport improvement.

In more recent experiments [5] the main ion species, deuterium, was diluted up to 30% relative to the electron density by injection of medium to low Z_i impurity gases (nitrogen or neon). The density was scanned to cover both the “linear confinement” (LOC) and saturated confinement (SOC) regimes with fixed B_T and I_p up to 1.2 MA ($q_{95} = 3.3$). As in previous experiments, phase contrast imaging (PCI) diagnostic showed significant reduction of turbulence due to dilution of the main deuterium ion population and at the same time, the ion thermal diffusivity was reduced by factors of up to 3 in the plasma core at $0.6 < r/a < 0.9$ as predicted by the TGLF code [3]. Comparisons between gyrokinetic code predictions (GYRO) based on synthetic diagnostic methods compared favorably with the measured fluctuating density spectrum by the calibrated PCI diagnostic. Dilution by nitrogen seeding was found to decrease the ion temperature gradient scale lengths in the outer regions of the plasma where ITG modes were dominant. In this paper we report new results from experiments by injecting neon that may be more adoptable to ITER due to less impact on tritium retention in the walls. The results obtained were very similar to the nitrogen seeding experiments: the ion heat transport was reduced, neutron production increased due to the higher ion temperatures, effectively mitigating the increased radiative losses due to the higher Z_i of neon, while the ohmic input power and the overall global confinement remained unchanged. Below we compare overall results from both nitrogen and neon seeding experiments and find similar impact on transport from dilution.

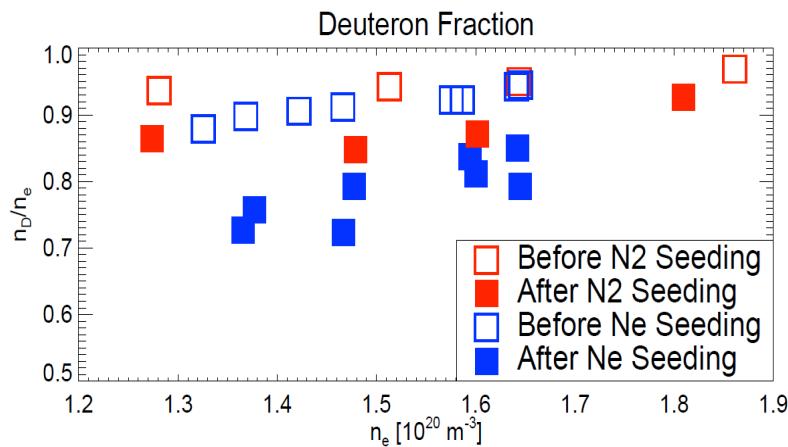


Fig. 2. Neon seeding diluted more than nitrogen seeding due to larger change in Z_{eff} . The neon seeding significantly reduced the amount of intrinsic impurities in the plasma, so the average impurity charge is close to 10, or purely neon. This may be explained by the neon seeding cooling the edge and reducing sputtering.

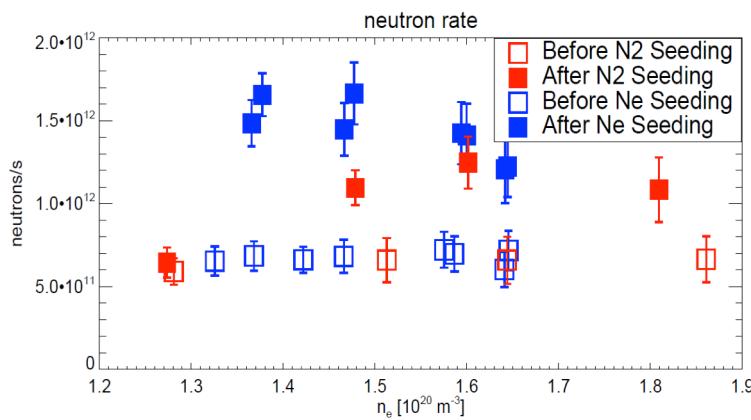


Fig. 3. Both nitrogen and neon seeding substantially increased the neutron rate (T_i increased by about 10%) in spite of the reduction of the fuel density. The increase of the neutron rate with seeding was in spite of the absence of change in the ohmic power input as shown in Fig. 4.

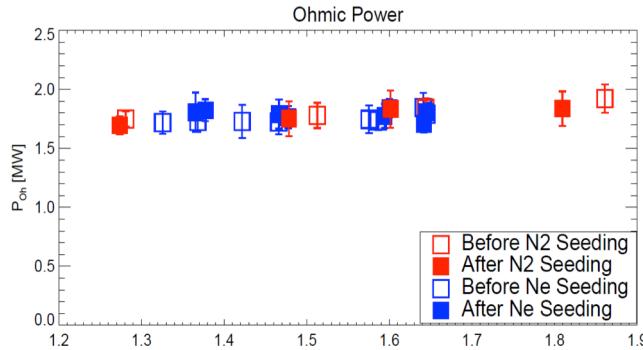


Fig. 4. Change in ohmic power with seeding was found to be negligible and cannot explain the increase in the neutron rate. Hence, profile effects must play an important role in the core plasma, including possible radial variation of the impurity ion density.

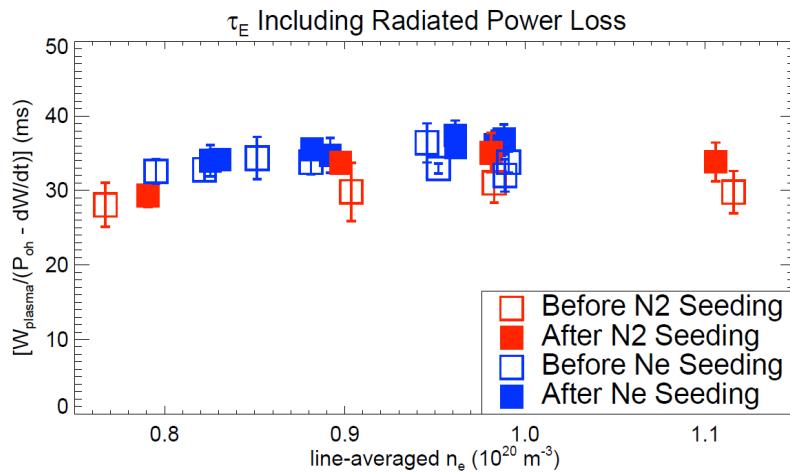


Fig. 5. Importantly, neither nitrogen nor neon seeding improved the overall energy confinement. This is in spite of the increased radiative losses by the impurity ions. This is consistent that the improved core ion confinement due to the reduction of turbulent diffusion.

It is important to note that the above results are consistent with reduction of turbulence in the outer plasma layers ($r/a = 0.8$, as verified by reflectometry) due to seeding as measured by phase contrast imaging diagnostic [5]. Results in both LOC and SOC regimes are summarized in Fig 6 below. Therefore the improvement in confinement is consistent with turbulence reduction.

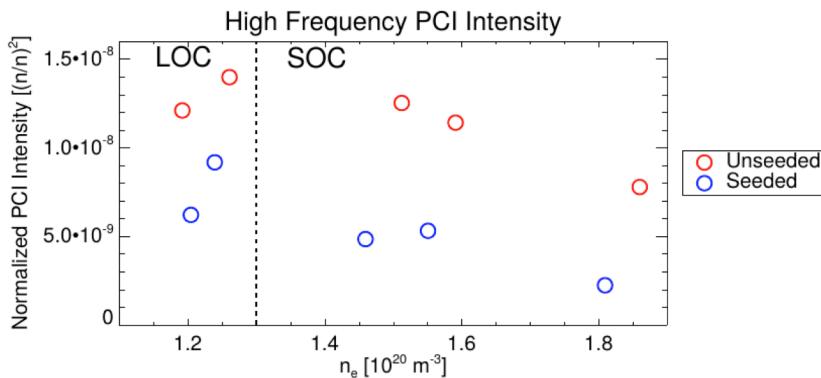


Fig. 6. Example of reduction of turbulence due to seeding with nitrogen at high frequencies ($f > 150$ kHz).

References

- [1] M Porkolab, J. Dorris, P. Ennever, et al., *Plasma Phys. Control. Fusion* **54**, 124029 (2012)
- [2] J. Candy and R. E. Waltz, *J. Comput. Phys.* **186**, 545 (2003)
- [3] G. M. Staebler, J. E. Kinsey, and R. E. Waltz, *Phys. Plasmas* **14**, 055909 (2007)
- [4] P.T. Ennever, M. Porkolab, J. Candy, et al., *Phys. Plasmas* **22**, 072507 (2015)
- [5] P.T. Ennever, M. Porkolab, J. Candy, et al., *Phys. Plasmas* **23**, 082509 (2016).

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