Article:

Reinke, M. L. orcid.org/0000-0003-4413-9613, Lore, J. D., Terry, J. T. et al. (7 more authors) (2017) Impact of perturbative, non-axisymmetric impurity fueling on Alcator C-Mod H-modes. Plasma Physics and Controlled Fusion. 122002. pp. 1-6. ISSN: 1361-6587

https://doi.org/10.1088/1361-6587/aa8d00

Impact of Perturbative, Non-Axisymmetric Impurity Fueling on Alcator C-Mod H-Modes

[1]M.L. Reinke, [1]J.D. Lore, [2]J. Terry, [2]D. Brunner,[2]B. LaBombard, [3]B. Lipschultz, [2]A. Hubbard, [2]J.W. Hughes, [2]R. Mumgaard, and [4]R.A. Pitts

[1]Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[2]MIT Plasma Science and Fusion Center, Cambridge, MA 02135, USA
[3]York Plasma Institute, University of York, Heslington, York YO10 5DQ, UK
[4]ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France

E-mail: mlreinke@psfc.mit.edu

PPCFDATE

Abstract. Experiments on Alcator C-Mod have been performed to investigate the impact of toroidally localized impurity injection on H-mode exhaust scenarios. Results help to inform sub-divertor gas injector designs, in particular that of the ITER machine, for which this work was primarily undertaken. In repeated EDA H-modes, the amount of N_2 injected into the private flux region was scanned up to levels which strongly impacted normalized energy confinement, H_{98}, and led to an H/L back-transition. Repeated scans increased the toroidal peaking of the gas injection, reducing from five equally spaced locations to a single toroidal and poloidal injector. Results show the impact on the pedestal and core plasma is similar between all cases as long as the total gas injection rate is held constant. An influence on toroidally localized impurity spectroscopy is shown, demonstrating a complication in using such data in interpreting experiments and supporting boundary modeling in cases where there are localized extrinsic or intrinsic impurity sources. These results, along with prior work in this area on Alcator C-Mod, form a comprehensive set of L-mode and H-mode data to be used for validation of 3D boundary physics codes.

Submitted to: *Plasma Phys. Control. Fusion*

1. Introduction

The need to mitigate particle and power fluxes to plasma facing components (PFCs) has been shown to be necessary in a reactor environment to ensure the survival of solid, metallic PFCs [1]. Many tokamaks have demonstrated the method of seeding the plasma with impurities to reduce the power to surfaces through inelastic electron-ion collisions resulting in line radiation [2][3][4][5]. This reduces the plasma temperature at the surface, which can be sufficient to enhance momentum loss from the plasma, dropping the pressure and leading to detachment. This picture is complicated by the geometry of the divertor, discrete PFCs and localized particle sources and sinks. Normally it is assumed that the tokamak is axisymmetric, but engineering realities lead to a 3D plasma material interaction. Present experiments can be used to help inform what 3D features are important in determining the plasma response.

Prior work on Alcator C-Mod explored the use of non-axisymmetric puffing of impurities in the divertor of Ohmic [6][7] and EDA H-mode plasmas [8]. A set of toroidally and poloidally localized gas injectors, described in more detail in [9], can be used to alter the toroidal peaking of the private flux N_2 injection. In Ohmic plasmas, toroidal variations in the electron pressure at the target were observed, while in H-modes, there was no apparent toroidal peaking in the amount of heat flux reduction to the outer target. Both experiments revealed a number of spectroscopic emission observations that indicated toroidal variation.

New experiments, presented here, explore the EDA H-mode configuration in [8] at higher seeding levels which lead to confinement degradation and H/L back-transition. H_{98} was reduced from $\sim$0.92 prior to introducing impurities to < 0.7 at the highest N_2 fueling rates. Results show little dependence of this result on the toroidal peaking of the nitrogen as long as the total gas injection rate into the torus is nominally the same. Measurements show H_{98} strongly correlated with electron pressure at the pedestal top, and both toroidal localized and nominally axisymmetric fueling follow similar trends. Thus, there appears to be no new physics mechanism(s) by which the non-axisymmetric fueling negatively impacts the confinement. A description of the experimental setup is given in Section 2 as well as in prior publications [8]. Section 3 compares the core and pedestal plasma response as the fueling is varied, while Section 4 discussions the context and implications of these observations.

2. Description of Experiments

Alcator C-Mod is a compact, high field tokamak that features bulk molybdenum for all PFCs and utilizes a vertical plate divertor [10]. The high field, 5.4 T in these experiments, enables access to high density and reactor-relevant parallel particle and heat fluxes, the latter reaching 0.4 GW/m^2 in H-modes prior to impurity seeding. In these plasmas, neutral pressures measured by Penning gauges in the divertor are measured to be $\sim$ 10 mTorr ($\sim$ 1.3 Pa) prior to impurity injection, rising to $\sim$ 25 mTorr after seeding. These ranges are at the lower end of those modeled to be desired for ITER [11]. The enhanced confinement regime used in these experiments is the EDA H-mode, which allows for stationary H-modes to be achieved without ELMs, with particle regulation being handled continuously by the quasi-coherent mode [12]. These qualities make the divertor regime a useful experimental demonstration of boundary physics relevant for ITER.

To investigate the impact of non-axisymmetric seeding, a set of five, toroidally spaced, and poloidally localized capillary gas injectors, shown in Figure 1, were configured with varying levels of toroidal peaking. In these tests, all five were first used together, providing qualitatively axisymmetric seeding reference cases, followed by a discharge with three neighboring injectors (those close to labeled for D, B and K ports) and finally a single location (near B). The total gas injected was adjusted by changing the plenum pressure between shots. The time history of the impurity influx rate was found by repeating the injection into an empty vacuum vessel, using the time evolution of the chamber pressure. This is shown in Figure 2, where 1 Torr-L/s is approximately 3.5×10^{19} molecules/s, so peak injection rates of 21 Torr-L/s would be just over 10^{22} el/s. An initial experiment used a coarse scan of the pressure to isolate the range of impurity influx which would impact the core confinement, followed by a fine scan which are the data shown here. Also apparent in Figure 1 is the cryopump in the upper divertor and the equilibrium is close to double null, with the outboard midplane distance between the primary and secondary separatrix being nominally 6 mm. While the gas injection in the lower divertor is not pumped directly, main chamber neutrals and far SOL flux are pumped, helping to maintain density and impurity control. This configuration is unlike ITER which will feature lower divertor fueling and pumping.

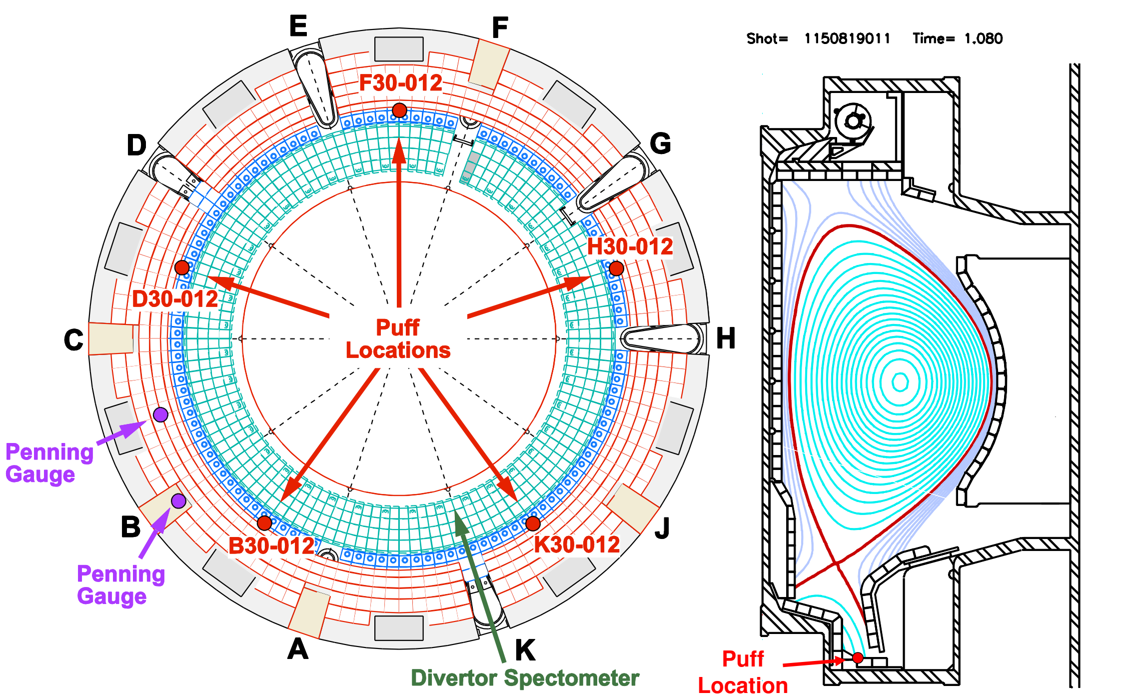

Figure 1: Layout of the private flux gas fueling relative to diagnostic locations (left) and the equilibrium used in these studies (right)

An example of the range of impacts on the plasma are shown in Figure 3. Here all five injection locations are used, and the qualitative features described below also occur in cases when fewer valves are actuated. Nitrogen is injected into an established

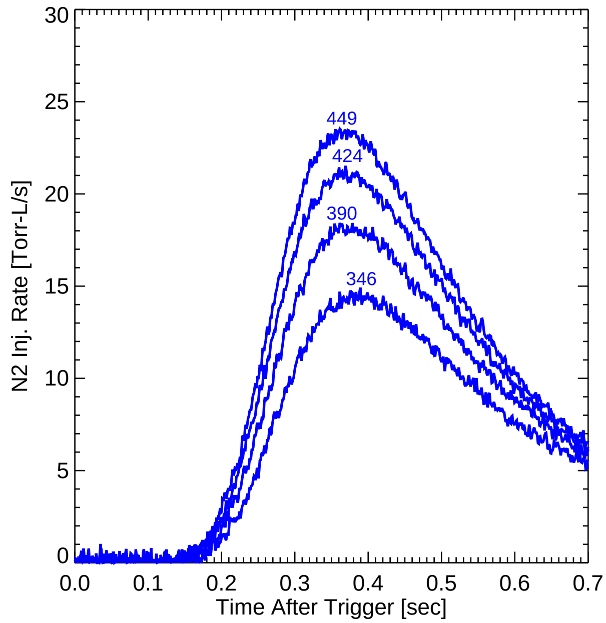

Figure 2: Time history of the N_2 injection rate when the system is setup to puff with x3 locations. Numbers near peaks are the plenum pressures used (in Torr).

H-mode, interacting with the plasma at $t \sim 1.0$ seconds. Target plasma configurations are the same as those used in [8], a 800 kA, 5.4 T EDA H-mode with a lower single null topology and the $B \times \nabla B$ drift direction towards the lower x-point. External deuterium fueling is used to control the pre H-mode density and no D_2 is injected after $t = 0.7$ seconds. Wall fueling, both divertor and main-chamber is known to play a strong role in C-Mod H-mode plasmas [13] [14]. Less ICRF power was available for these plasmas, $P_{RF} = 2.8$ MW compared to 3.5 MW in [8], resulting in pre-seeding H_{98} to be just above 0.9 instead of 1.0. It is known from prior work [15] that for similar EDA H-modes normalized energy confinement scales linearly with net input power up the maximum achieved in Alcator C-Mod, $P_{net} < 3.5$ MW with $P_{RF} \sim 5$ MW. The expectation is that the primary findings presented here would be similar at higher ICRF power, thus higher H_{98}, just requiring marginally more nitrogen.

The time histories shown in Figure 3 scan a variety of expected impacts as the seeding is increased, from weakly perturbing the confinement through causing intermittent H/L back-transitions. In all cases, the average heat flux to the outer divertor, $\langle q \rangle$, measured using surface thermocouples [16] is reduced to the effective error limit, $\sim$1 MW/m^2, prior to any change in the normalized confinement. As the plenum pressure and peak influx rate are increased, the core nitrogen increases, estimated via N VII 2p-1s line emission using a midplane, radially viewing VUV spectrometer [17], as does the line-averaged density from interferometry. At the lowest plenum pressures, confinement is weakly perturbed, partly through the density scaling in τ_{98}, but also through a slight increase in Ohmic input power, while the stored energy W_{MHD} stays constant. At the highest plenum pressures, a strong density rise is observed and H/L

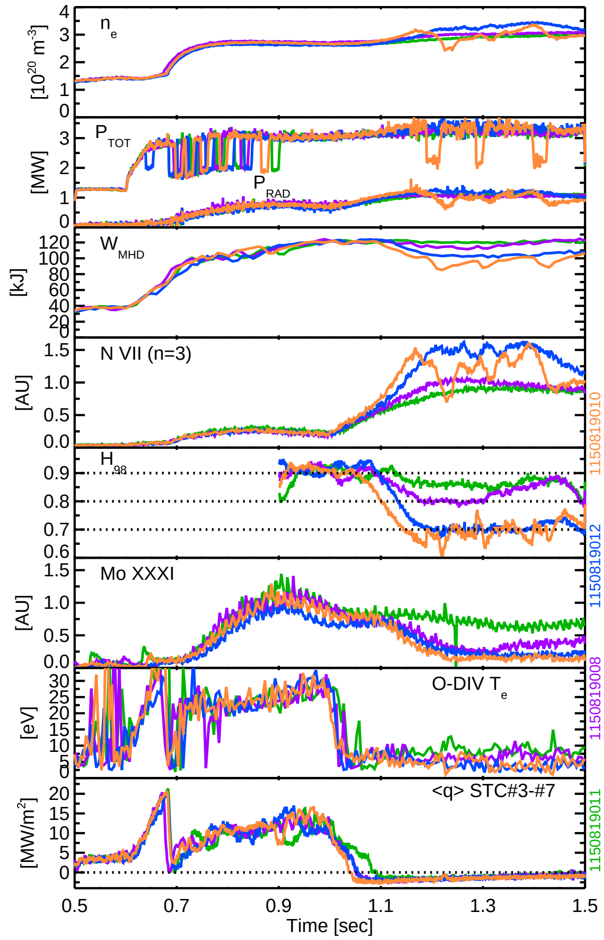

Figure 3: Evolution of the H-mode plasma response to varying levels N_2 injected using all five injection locations. Plenum pressures at 300 (green), 350 (purple), 365 (blue) and 388 (orange) Torr scan from weakly to strongly impacting the normalized energy confinement.

back-transitions occur which result in ICRF drop-outs. The confinement degrades quickly as the nitrogen influx is increased, going from $H_{98} \sim 0.8$ at 350 Torr to $H_{98} \sim 0.7$ at 365 Torr. Interestingly, and for reasons not known and not explored here, the core molybdenum content drops off suddenly as the nitrogen seeding is increased beyond the lowest seeding level. This occurred at all toroidal peaking configurations. Radiated power shown in Figure 3 is from a wide-angle viewing AXUV diode which does not effectively capture the divertor radiation, resulting in an under prediction of P_{RAD}/P_{TOT}.

3. Trends in Plasma and Confinement Response

Similar scans of nitrogen seeding as shown in Figure 3 (for all five injection locations) were repeated using three (D, B and K) and a single (B) injection location. These all showed similar drops in normalized confinement as the plenum pressure was increased, although the absolute pressure and single capillary throughput increased to compensate as the number of injection locations was reduced. This section investigates differences in the plasma response due these impurity fueling configurations.

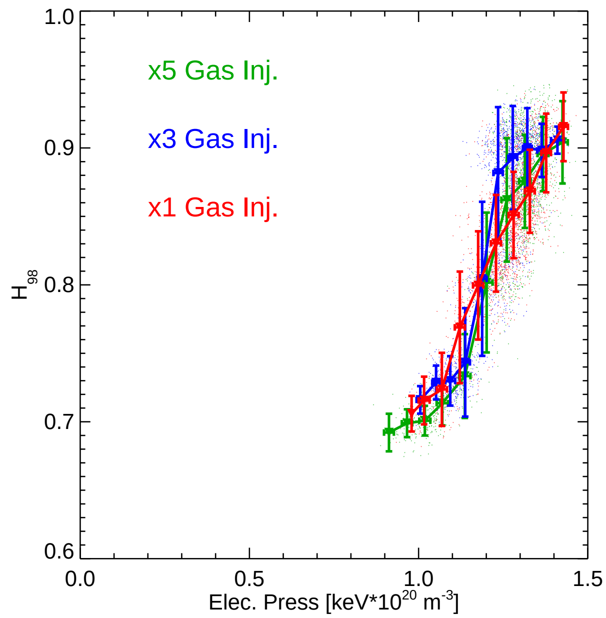

Figure 4: The evolution of the normalized confinement with electron pressure measured radially inside the top of the pedestal. A drop in H_{98} occurs at the same $p_{e,ped}$ for all seeding configurations.

From the perspective of the core, the confinement degradation is shown to be acting through the same process, a weakening of the pedestal, for all fueling setups. In Figure 4, a measure of the electron pedestal pressure, $p_{e,ped}$, with fast time resolution is constructed from the line-averaged density from the interferometer and the electron cyclotron emission temperature at $r/a = 0.85$. The dynamic evolution of the core confinement is tracked as the impurity injection causes a drop in H_{98} and in some cases recovers, as can be seen for the 350 Torr pressure case in Figure 3. The drop in $p_{e,ped}$ and the subsequent effect on core confinement has long been seen on C-Mod as an example of electron profile stiffness in plasmas with only an edge transport barrier [18][19]. The demonstration that all seeding configurations overlap and exemplify this trend, suggest that no new mechanism(s) are necessary to explain the impact on the core. It is likely, but not proven here, that the mechanism of $T_{e,ped}$ reduction is via impurity radiation. Full poloidal tomography of radiation from bolometry is not available on C-Mod. Radiation from charge states at/near the top of the pedestal ($T_e \sim 400$ eV) will come from H-like (N VII) and He-like (N VI) low-Z ionization stages. This is tracked by the VUV spectroscopy and plotted over the same dynamic data series, shown in Figure 5. Once gain, no difference is seen as the number of injection locations is varied. Together these results indicate that despite a varying 3D source, there are 0-D or 1-D metrics that repeatedly capture the core plasma impact, avoiding the need for higher dimensional models or more complicated diagnostics to observe the plasma and be tied into feedback control schemes.

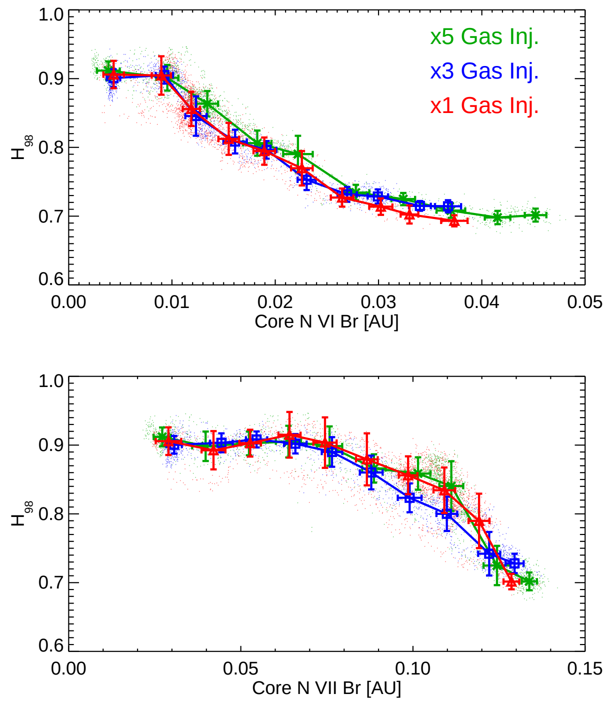

Figure 5: Response of H_{98} compared to changes in N VI (top) and N VII (bottom) emission (viewed radially at the midplane) is shown to be the same for all gas injection configurations.

It is important to measure the gas injection necessary to elicit the same core and pedestal response as the toroidal peaking factor changes. When comparing the instantaneous gas injection rates, shown in Figure 2, the dynamic change in core confinement does not yield constructive results due to the short duration of the seeded H-mode and substantial phase delay between gas injection and impact on the core. As shown by the recovery of H_{98} and drop in core N VII in the cases shown in Figure 3, the nitrogen behaves as a dominantly non-recycling impurity. Thus, we propose comparing the peak nitrogen injection rate to the drop in normalized confinement. Shown in Figure 6, a weak difference is observed in the total rate of nitrogen injection as the puffing becomes more toroidally localized. Increased plenum pressure, which was tuned empirically, translates into dramatically increasing the local gas injection rate while nominally maintaining the same total rate of gas flow into the torus. There is a response outside of the given error bars that indicates that slightly more nitrogen can be injected in the axisymmetric configuration and still maintain the same normalized confinement. This could translate to a marginally higher effective utilization of the gas, indicating an advantage, but other effects cannot be ruled out. For example, the axisymmetric seeding interacts with a wider range of PFC area. Thus, it could be that in the x5 Gas Injector data in Figure 6 has a marginally higher pumping, thus requiring a higher level of gas injection to achieve the same effective fueling rate into the plasma. Although this dataset was collected first during the day, the walls appear to be saturated by the three H-mode plasmas with nitrogen seeding run prior to the start of the x5 injector scan. Pre-injection N II (not shown) and N VII (Figure 3) do not evolve shot-to-shot and are relatively small fraction of the total nitrogen emission seen following the intra-shot introduction from the private flux region.

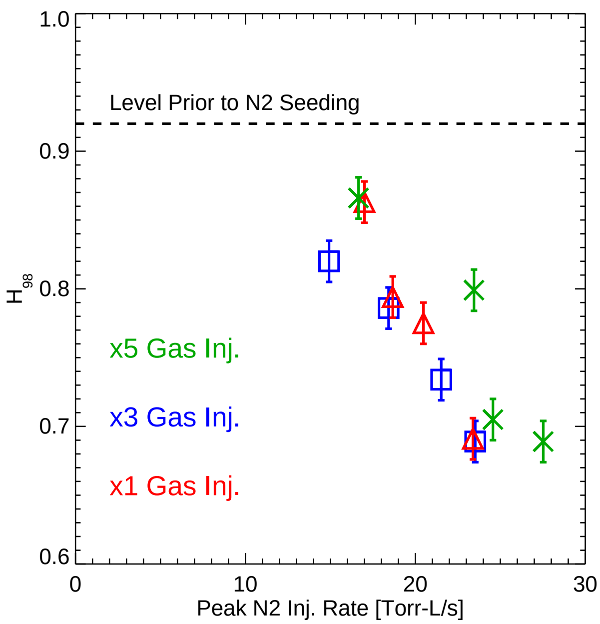

Figure 6: The H_{98} following nitrogen injection is compared to the peak injection rate, showing little difference between toroidally localized and axisymmetric seeding

4. Discussion

From Section 3 it is shown that increasing the toroidal localization of low-Z seeding does not impact the perturbative response on the edge and core plasma as long as the same total gas injection rate can be maintained. This provides an experimental basis for a simple design criterion for the total flow rate requirements of sub-divertor fueling systems like ITER [20] which will be by fed a few, discrete sectors. Requirements for redundancy suggest that each sector feed should be rated to carry the gas flow expected to be spread evenly between all sectors. Prior work [8] focused on the H-mode response at levels that resulted in heat flux mitigation, which also featured similar reductions in electron temperature. The present study intended to extend the C-Mod experiments into the pronounced or fully detached regime of the outboard target. In all cases, the inner divertor before and after seeding is partially, but not fully detached, with $T_e < 10$ eV, and a few eV rise in the far SOL, $\rho \sim 10$ mm mapped to the outboard midplane, after seeding is applied. For the plasmas shown in Figure 3, measurements of electron temperature at the outer divertor indicate $25 < T_e < 30$ eV prior to seeding. For $\rho < 5$ mm this drops to $T_e < 10$ eV during seeding and reaches below 5 eV at the higher seeding levels, for example 3.7 ± 1.2 eV is measured in 1150819012 shown in Figure 3. Complementary analysis of the density at the target that address the degree and extent of the outer divertor detachment have not been presented here due to possibly misleading Langmuir probe measurements [21]. However, they are argued to be unnecessary to support the immediate conclusion highlighted by Figure 6. The impurity gas injection was increased to push the H-mode up to and past the H/L back-transition as shown at the highest plenum pressure in Figure 3. This resulted in a plasma response similar to other detachment studies [22][23], shown by changes in pedestal temperature and line-averaged density. Additionally there are non-linear effects at work, with strong differences in plasma response resulting from $\sim 5\%$ changes in plenum pressure. Despite this, the total gas injection rate remains a reliable ordering as the toroidal peaking is varied. It remains of interest to the boundary community to understand the progression and causal links between confinement degradation and divertor detachment, and this dataset and complementary experiments will be used to investigate this further in future work.

Presently, because of the lack of recombination physics in EMC3[24], there is no tool that can model these experiments. Thus, to fully understand if the results shown here can be extrapolated to ITER requires additional advancements in our boundary modeling capability. Any eventual validation effort should not focus on understanding the absolute number of Torr-L/s that is required to sustain a particular C-Mod plasma but examine if there is any significant difference in simulated response as the toroidal peaking is varied. The former may end up being something difficult or impossible to accurately model due to puffing/pumping geometry, including degree of particle loading in the PFCs as well as the self-consistent plasma response. In contrast, the latter addresses a more transferable question of plasma physics which a 3D boundary simulation could access: given a range of boundary conditions, is the plasma response the same as the peaking is varied at fixed total gas injection?

This work also informs other Alcator C-Mod experiments where a single, high-throughput and feedback controllable gas injector was used [16]. The majority of evidence shows the evolution of the surface quantities has no strong systematic errors due to the lack of axisymmetry of impurity injection. This is shown to not extend to portions of the visible plasma spectrum. Figure 7 shows changes in N II emission from the dataset in [8], which fed nitrogen into a each toroidal gas injector on subsequent shots. This allowed the toroidal variation in the emission to be explored by fixed spectroscopy diagnostics, shown in Figure 1. Ten shots in total were taken, completing two toroidal scans which show good repeatability. Multiple viewing chords are averaged together to view the various divertor regions, and only the increase above pre-injection background is considered. These changes in brightness are normalized to the average change seen from all toroidal locations. While higher ionization stages indicated weaker toroidal peaking, N II shows clear non-axisymmetric structure in all regions of the divertor. Thus if visible spectroscopy data are to be used in drawing empirical conclusions or constraining boundary modeling, care should be taken to ensure as much as possible

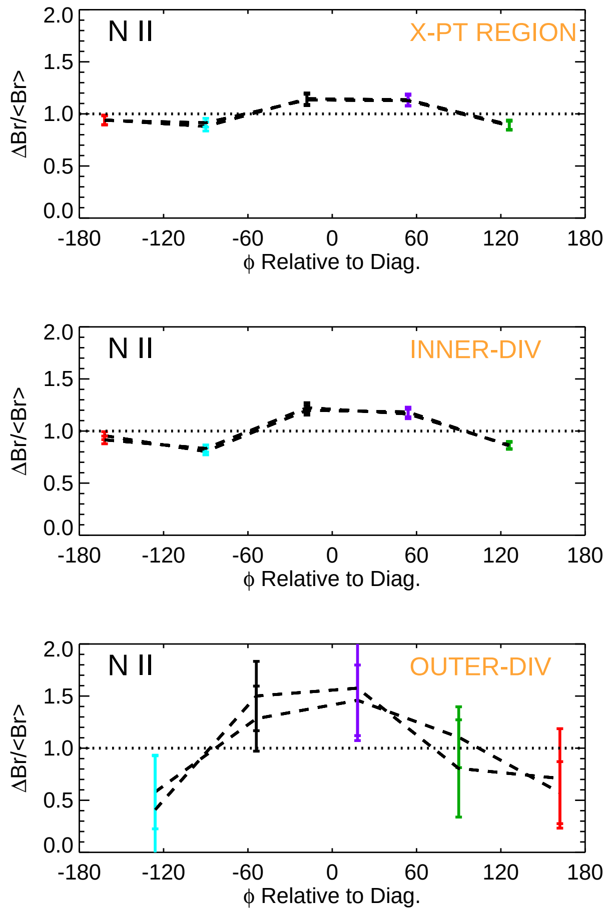

Figure 7: Demonstration of toroidal variation in weakly ionized nitrogen emission for a single toroidal gas injector.

to ensure that the injection can be made axisymmetric. This result is also presumed to extend to cases where leading edges or PFC misalignment can create a 3D impurity source.

In summary, new experiments on Alcator C-Mod have extended prior work on the impact of non-axisymmetric impurity seeding in EDA H-modes to higher levels of total impurity influx. This now includes the regime where strong reductions in normalized energy confinement are observed along with H/L back-transitions. It is demonstrated that as the gas puffing becomes more toroidally localized, the plasma response is similar if the total gas injection rate is kept constant. The dynamic evolution of the confinement is correlated with changes in the pedestal top pressure, indicating a stiffness mechanism, that is the same for all toroidal peaking configurations. This indicates that no new mechanism(s) for confinement reduction are initiated as the axisymmetry is varied, allowing conventional 0-D or 1-D analysis and control techniques to be used over a wide range of extrinsic impurity seeding configurations. Impacts on toroidally localized spectroscopic emission are highlighted which could impact validation of boundary modeling.

5. Acknowledgments

The authors would like to thank the C-Mod team for expert operation of the facility, and MR would like to highlight the patience of Maria Silveira in configuring the gas injection system for this experiment. This work is supported in part by U.S. Department of Energy award DE-AC05-00OR22725 and DE-FC02-99ER54512, using Alcator C-Mod, a DOE Office of Science User Facility. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization. BL was funded in part by the Wolfson Foundation and UK Royal Society through a Royal Society Wolfson Research Merit Award as well as by the RCUK Energy Programme (EPSRC grant number EP/I501045).

6. References

[1] P.C. Stangeby, A.W. Leonard. *Nucl. Fusion*, 51:063001, 2011.
[2] A. Kallenbach, *et al*. *Nucl. Fusion*, 55:053026, 2015.
[3] A. Loarte, *et al*. *Phys. Plasmas*, 18:056105, 2011.
[4] M. Fenstermacher, *et al*. *Phys. Plasmas*, 4:1761, 1997.
[5] J. Rapp, *et al*. *Nucl. Fusion*, 44:312, 2004.
[6] J. Lore, *et al*. *J. Nucl. Mater*, 463:515, 2015.
[7] M.L. Reinke. Observation of 3d radiation structure from poloidally and toroidally localized nitrogen puffing in alcator c-mod ohmic plasmas. Technical Report PSFC/RR-14-3, MIT - Plasma Science and Fusion Center.
[8] J. Lore, *et al*. *Phys. Plasmas*, 22:056106, 2015.
[9] D. Jablonski. *Local gas injection as a scrape-off layer diagnostic on Alcator C-Mod*. PhD thesis, Massachusetts Inst. of Tech., 1996.
[10] E. Marmer, *et al*. *Fusion Sci. Tech.*, 51:261, 2007.
[11] A.S. Kukushkin and H.D. Pacher. *Nucl. Fusion*, 56:126012, 2016.
[12] M. Greenwald, *et al*. *Fusion Sci. Tech.*, 51:266, 2007.
[13] B. LaBombard, *et al*. *Nucl. Fusion*, 40:2041, 2000.
[14] J.W. Hughes, *et al*. *Nucl. Fusion*, 47:1057, 2007.
[15] J.W. Hughes, *et al*. *Nucl. Fusion*, 51:083007, 2011.
[16] D. Brunner, *et al*. *Rev. Sci. Instrum.*, 87:023504, 2016.
[17] M.L. Reinke, *et al*. *Rev. Sci. Instrum.*, 81:10D736, 2010.
[18] J.W. Hughes, *et al*. *Phys. Plasmas*, 9:3019, 2002.
[19] A. Hubbard, *et al*. Pedestals and confinement in alcator c-mod h-modes. *Proceedings of 26th EPS Conf. on Control. Fusion and Plasma Physics*, 23J:13, 1999.
[20] Y. Yang, *et al*. *Fusion Eng. Design*, 85:2292, 2010.
[21] D. Brunner, *et al*. *J. Nucl. Mater.*, 438:S1196, 2013.
[22] A. Kallenbach *et al*. *Nucl. Fusion*, 55:053026, 2015.
[23] J. Goetz *et al*. *Phys. Plasmas*, 6:1899, 1999.
[24] Y. Feng*et al*. *J. Nucl. Mater.*, 241:930, 1997.