1. Purpose of Experiments
It has been widely reported that on JET when operating with a metallic wall as opposed to a carbon wall there is a 30-40% reduction in performance [Beurskens2013, Giroud2013]. This performance can be partially recovered with nitrogen seeding. Experiments performed at AUG have also shown to increase confinement when nitrogen seeding is used [Schweinzer2011, Kallenbach2013]. However, due to operational constraints associated with tritium handling, nitrogen cannot be used in JET DT operation. While nitrogen operation is planned for ITER, a non-reactive divertor radiator, such as neon, is preferable. More recent JET results, which report on neon as an alternative seeding impurity, demonstrate no improvement in performance [Giroud2014]. In addition, the injection of deuterium gas necessary to control the tungsten concentration in the confined plasma and maintain fuel purity is reported to lower the attainable pedestal pressure. So far, the mechanism(s) responsible for this are not understood by theory [Leyland2015, Saarelma2015]. The focus at JET is to develop a DT compatible integrated scenario. Part of the challenge is to understand how to use differences

Pedestal pressure vs ratio of divertor over main plasma radiation in JET ELMy H-mode plasmas without seeding and with N or Ne seeding for various D gas rate and at two input power [GiroudIAEA2014].
between low-Z impurities such as nitrogen and neon in improving pedestal confinement. Demonstrating a physics understanding is critical in predicting the pedestal pressure in ITER.

The goal of this experiment is to address the role of main ion fuelling on the pedestal together with decoupling the role of impurity content in the pedestal and radiation in the divertor, two of the largest factors thought to impact the confinement improvement (or eventually degradation) with impurity seeding. In particular, the data would be used to benchmark linear MHD analysis and also serve as input for testing confinement improvement theories.

2. Background

Discuss Physics Basis of the proposed research. Prior results at Alcator or elsewhere, and any related work being carried out separately.

When operating in ELMy H-mode with metal walls, a deuterium gas puff is typically required to tailor the ELM frequency to prevent the buildup of high-Z impurities. In JET and AUG, this typically results in a broadened pedestal and a lowered attainable pedestal top [Beurskens2013]. C-Mod has also reported a lack of response of the density pedestal in EDA H-mode to external gas puffing but noted a decrease of the temperature pedestal top [Hughes2007]. A similar response is seen in discharges with high neutral density due to PFC outgassing following boronization [Hughes 2011]. In addition, when large amounts of fuelling gas are puffed, current theories describing the pedestal (linear peeling-ballooning modes or the EPED predictive model) are no longer able to accurately describe the form of the pedestal [Leyland2015, Maggi2014]. Investigating and understanding this phenomenon will be important before ITER operation commences. It is, as of yet, unclear whether this is an effect which is purely in the pedestal or if it is a combined pedestal/scrape-off layer effect, with the SOL acting as a boundary condition on the pedestal.

Such effects can lead to a reduction of the global performance of H-mode plasmas in metal-walled devices with respect to devices with a carbon wall. In addition, the decrease in low-Z impurity content may also play a role in the reduced confinement. Reintroducing low-Z impurities such as carbon (in the form of CD₄) and nitrogen can help recover the thermal stored energy. This recovery is largely due to a recovery of the pedestal pressure, which propagates to the core through profile stiffness. In JET this has so far been investigated in low \( \beta_N<1.5 \) plasmas at both low (\( \delta \sim 0.2 \)) and high triangularity (\( \delta \sim 0.4 \)) where with N₂ seeding the pedestal pressure (and mainly temperature) was increased by 10% and 40% respectively. In AUG, seeding N₂ and CD₄ in high \( \beta_N \sim 2 \) plasmas lead to a pedestal pressure improvement of up to 40% whether at low or high plasma triangularity, and resulting from a temperature pedestal increase at a same net input power (input power minus radiative power inside the last closed flux surface). In Alcator C-Mod impurity seeding with N₂ or Ne did increase the pedestal confinement in EDA H-mode plasmas (\( \beta_N \sim 1.3 \)) but did so indirectly, increasing the ICRF power coupled to the plasma and raising the net input power via reduction in core molybdenum content and increase in net input power [Reinke2011, Loarte2011, Hughes2011]. The net input power is then increased in comparison to the unseeded H-mode.

The SOL acting as a boundary condition on the pedestal is one of the main ideas being explored in this series of experiments, which has analogues on other devices. One of the basic
working ideas for confinement improvement in Type-I ELMy H-modes is that the impurity content in the pedestal transiently decreases the edge current density, allowing the pressure gradient or pedestal top pressure rise to higher values. Since the core beta also has a stabilizing effect on the pedestal, this creates a positive feedback loop [Citrin2014]. Other ideas involve the SOL as a boundary condition on the pedestal, with divertor conditions acting to influence the plasma fuelling; the exact mechanisms of confinement enhancement or degradation with impurity seeding and neutral fuelling are currently unknown. It is hoped that this series of experiments will shed light on this important topic.

Additional experiments on AUG with helium puffing have shown a significant (~20%) degradation of confinement [Neu2008, Dunne2014] with reactor relevant levels of helium in the plasma. However, it was also observed that the confinement begins to drop as soon as there is a noticable level of helium in the plasma. The stark contrast in the effect of He with nitrogen and neon leads to several questions regarding the dominant driving mechanism for confinement improvement (or degradation). Helium is separated from neon and nitrogen in both its contribution to $Z_{eff}$ (a larger amount, and hence more dilution, is required for the same $Z_{eff}$), and amount of radiation; nitrogen radiates strongly in the divertor, while helium has almost no effect.

3. Approach
Describe the methodology to be employed; explain the rationale for the choice of parameters, etc. Describe the analysis techniques to be employed in interpreting the data, if applicable. If the approach is standard or otherwise self-evident, this section may be absorbed into the Experimental Plan.

For this work, the aim is to carefully document the confinement, pedestal properties, ELM frequency and size (both amplitude and length) and divertor conditions in ELMy H-mode plasma with deuterium gas and N or Ne seeding. Two run days are planned, the first using nitrogen seeding which has been demonstrated to have favorable impact on JET, but leads to difficulties in diagnosing the pedestal on C-Mod due to pedestal CXRS contamination. A second day using neon seeding will follow to provide more detailed documentation of changes in the pedestal and examine any differences in the seeding species. If time allows, the dependence of the transition from EDA H-mode to ELMy H-mode on impurity composition will be investigated. A reference in EDA H-mode in the same shape as ELMy H-mode could be gathered if possible for comparison with previous C-Mod work [Hughes2011, Loarte2011,Reinke2011].

The experimental strategy is informed by unseeded plasmas obtained in experiments by A. Diallo, (MP 754). One common shape (JFT-2M shape) will be used for the EDA H-mode and ELMy H-mode with moderate elongation (kappa <=1.55), a weak shaped crown (delta_u~0.2) and an outer strike point in the divertor slot, which has previously been demonstrated to allow access to Type I ELMs.

In order to obtain steady H-modes with reduced high-Z impurities, an overnight boronization will be required before each run day. Thus several shots of boronization recovery will be needed in the morning of the experiments and the initial H-modes will have a large amount of wall fueling. Advantage will be taken to achieve high-collisionality EDA H-modes early
in the run, then transition to ELMy H-mode by gradually reducing the plasma density throughout the day.

On each run day, the most important part of the experiment will be to explore the effect of D-gas, extrinsic low-Z impurity seeding and $\beta_N$ (via RF power) on the ELMy H-mode pedestal and global confinement. We will explore ELMy H-mode at two different pedestal densities and three input powers to achieve a range of $\beta_N$ values. Care should be taken to have an overlap of $P_{\text{net}}$ values between the seeded and unseeded discharges. The first day will be dedicated to nitrogen and mostly setup pulses. The second day will be dedicated to neon and, if time allows, He in order to make a connection with other devices and to establish a $Z$/radiation dependence of the impact of impurities on confinement.

Profiles in ELMy H-mode must be analyzed according to their timing within the ELM cycle. We would rely on the python tools imported from GA by T. Osborne.

Successful completion of the experiment will result in accurate pedestal and core temperature, density profiles, $Z_{\text{eff}}$ values, allowing determination of profile peaking, linear stability analysis using interpretative and predictive tools and also some characterization of the divertor conditions.

4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:
- **Toroidal Field**: 5.4T
- **Plasma Current**: 0.9MA
- **Working Gas Species**: D$_2$
- **Density**: $\sim 1 - 3 \times 10^{20} \text{m}^{-3}$

**Boronization Requested** (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): yes overnight prior to each run day

**Equilibrium configuration** (if possible, refer to database equilibria): LSN, with outer strike point in slot, and weakly shaped crown. Nominally begin with 1140826007: kappa<=$1.55$, delta$_u$$\sim 0.2$, delta$_l$$\sim 0.8$

4.2 Auxiliary Systems

- **ICRF Power**, pulse length, phasing: 2—5MW, D(H) heating
- **LHCD Power**, pulse length, phasing: no
- **Pellet Injection** (species): no
- **Impurity blow-off injection**: no
- **Diagnostic Neutral Beam**: if available
- **Special gas puffing**: NINJA with D2 for CXRS, H-BOT Ar for HIREXSR B-SIDE LOWER with N,Ne,He for impurity seeding
- **Cryopump**: no
- **Non-axisymmetric Coils** (Connections, Current); standard error field correction
- **Other**: 
4.3 Diagnostics
List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

\( T_i \): core (HIREXSR) and edge (gas puff CXRS system):
Thomson system for core and edge \( T_e \) and \( N_e \), and SOL densities
O-mode reflectometry for SOL \( n_e \) (if available)

**ELM dynamics**: ECE, D-alpha, B-Port Ly-alpha

**Edge Er**: gas puff CXRS system for unseeded and Ne seeded discharge. If N grating then also for N seeded discharges.

**Bolometry**: midplane and divertor, AXUV diodes

**XTOMO**: edge SXR for mode in pedestal.

**Pedestal turbulence diagnostics**: X-mode reflectometry, fast magnetics, PCI (if available)

**Divertor spectroscopy**: CHROMEX & CXRS with K-TOP, K-BOT and A-BOT views, emphasis will be on the localization of the species indicating conditions of divertor detachment in ELMy H-mode.

**Dilution**: ZAVE and neutron rate

**Core spectroscopy**: XEUS, LoWEUS

**Neutral densities**: main chamber and divertor neutral pressure gauges

5. Experimental Plan
Both sections must be filled in.

5.1 Run sequence Plan
Specify total number of runs required and any special requirements, such as consecutive days, no Monday runs, run period – 10 hours maximum – etc.

Two runs are requested with similar run plans, with day one being N\(_2\) seeding and day two being Ne seeding and possibly He.

**Before the run day**: the shape has been run, the critical density for transition from EDA to ELM\(_y\) H-mode is known (taken from 1140826 run). Maximum RF power that can be injected in plasma 2.1 and 3.1 is known.

**For first run day:**

1. Boronization recovery, ICRF conditioning and H-mode demonstration. The first H-modes will be high-density EDA H-modes. Establish unseeded target plasma based on 114826007. Ramp ICRF from 2.0-4.0 MW from 0.7-1.5 seconds (2-3 shots).

   1.1. Set-up/check all key diagnostics listed above
1.2. Begin optimizing passive diagnostics, NINJA puffs for CXRS, Ar for HIREXSR, CHROMEX channel layout. Ideally once the line-of-sight have been selected, no change should be made during the rest of the runs.

2. (whilst waiting for the density to drop) At target EDA density to be determined, perform nitrogen scan at high RF power

2.1. Shot-to-shot, increase B-SIDE LOWER N₂ flux from trace to level perturbing confinement

3. Reduce target density to transition to ELMy H-mode, remove impurity seeding. Achieve a suitable ELMy H-mode at target density (target density 1 on figure 2). (not sure how many shot needed to achieve this) (10 shots)

3.1. Obtain reference ELMy H-mode plasma at target density 1 with minimum RF power for betaN of 1.

3.2. Increase RF power or reduce depending to achieve maximum range of beta (target betaN~2 if possible):

3.3. Scoping discharge to determine the three seeding rate needed:

   • Ramp (or staircase waveform) in N seeding in target plasma 3.1, to determine when N seeding lead to detachment → determine 3 seeding levels, the last one close to level needed for detachment.

3.4. Run discharge 3.1 with constant seeding rate 1, rate 2, and rate 3 (3 shots+ 1 setup): adjust N seeding waveform for constant N flow in first shot, adjust RF power to match PNET of 3.1

3.5. Run discharge 3.2 with constant seeding rate 1, rate 2, and rate 3 (3 shots), adjust RF power to match PNET of 3.2

4. Reduce ELMy H-mode density further to target density 2, w/o seeding until target density level 2 (see figure 2) (8 shots)

4.1. Obtain reference ELMy H-mode plasma at target density 2 with same RF power as 3.1.

4.2. Run discharge with same RF power as 3.2

4.3. Run discharge 4.1 with constant seeding rate 1, rate 2, and rate 3 (3 shots), adjust RF power to match PNET of 4.1

4.4. Run discharge 4.2 with constant seeding rate 1, rate 2, and rate 3 (3 shots), adjust RF power to match PNET of 4.2

5. (if time and if data not obtained already) Test if transition from EDA to H-mode is dependent on the plasma impurity composition (4 shots)

   If impurity injection reduces the pedestal density then option 5.1
If impurity injection increases the pedestal density then option 5.2

5.1. Raise L-mode target density with feedback, to reach EDA H-mode close to characteristic density for transition to ELMy H-mode

- Run discharge 5.1 with constant seeding rate 1, rate 2, and rate 3 (3 shots)

5.2. Raise L-mode target density, to reach ELMy H-mode close to characteristic density for transition to ELMy H-mode

- Run discharge 5.2 with constant seeding rate 1, rate 2, and rate 3 (3 shots)

6. (if time) Inject seeded gas from divertor for checking impact of a divertor impurity source on the result. (2 shots)

7. (if time and data not obtained already) Raise the L-mode target density to reach EDA H-mode at target density to be defined: (4 shots)

- Run discharge 7 with constant seeding rate 1, rate 2, and rate 3 (3 shots)

8. (if time) Active D fuelling during the main heating phase to compare with D outgassing, N seeding scan – 2 D fuelling levels with 2 nitrogen levels at constant input power (2 shots)

9. (if time) EDA H-mode in vertical target: nitrogen scan with given RF power up to detachment: good LP data (sweep maybe needed),

For the second day: Ne will be investigated as was N in the first run day and if time allows also an additional impurity such as He.

Figure 2: Original figure extracted from Hughes NF 2011. The target density in ELMy H-mode are shown in dashed line as density 1 and density 2. The red and blue circle show the hypothesis position of unseeded ELMy H-mode discharges at low and high RF power respectively. The green lines show the possible trajectories of 3 consecutive discharges with increasing seeding rate from unseeded references discharges. The target density 3 correspond to EDA H-mode that could be run on day 1 if time allows.
6. Anticipated Results
Discuss possible experimental outcomes and implications. Indicate if the program may be expected to lead to publications, milestone completions, improved operating techniques, etc. Indicate if the experiments are intended to contribute to a joint research effort, an ITER request, or an external database.

The results of this program are expected to lead to at least one publication on the impact of impurities on confinement in ELMy H-modes in Alcator C-Mod, including a comparison to the already established effects in EDA H-mode. Additionally, since these experiments are foreseen as part of an ITPA joint experiment, it is also planned that they will form the basis for an inter-machine comparison of the effects of impurities in different devices. In particular, a comparison with the other metal-walled devices AUG and JET is planned.

7. References
Include references both to external and internal literature or communications which bear on this proposal. See Section 2.


[Dunne2014] Dunne et al., Impurity seeded H-mode experiments ITPA PEP meeting, Cadarache, France, October 2014