1. Purpose of Experiments
Include immediate goal of the experiments, scientific importance and/or programmatic relevance. Refer to any relevant program milestones.

This experiment aims to explore and understand the transitions from I-mode to H-mode which have been observed to occur as density is increased, with a density limit dependent on heating power. This is a key limit to I-mode operation, which will affect the extrapolation to ITER, SPARC and other fusion devices. It aims to document, and perhaps extend, the upper ranges of density (both absolute and normalized) for I-mode operation and what is happening at a fluctuations/flows level which leads to these transitions. It follows up on the successful experiments in MP 712 and 746.

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

The I-mode regime has been developed on C-Mod into a robust, high confinement regime with pedestals and normalized confinement reaching or exceeding that of H-mode. The best access and performance has been found to be with reversed field, lower null discharges; in many cases I-mode has then been sustained up to the maximum available power, with no H-mode transitions. [Hubbard IAEA 2012].

There is an optimal density window for accessing I-mode, typically between about 1.1 and 1.6e20 m⁻³ (nebar). Below this density, L-I threshold rise, as do impurities. At some point plasmas just stay in L-mode. At higher density, plasmas transition directly from L-mode to H-mode, with at most a short, transient, I-mode phase.
However, once the I-mode is formed, one can increase the density by simultaneously heating and fuelling. This was tried on a few shots on 1120907, and worked immediately. Fig. 1 shows an example – only the second attempt (1120907032) where gas puffing was added (pre-programmed) at 0.9 secs. A 30% increase of density was achieved, to nebar 2.0e20 m$^{-3}$.

Densification was further explored in a dedicated MP 746. We succeeded in reproducing the result, but, to our disappointment, not in significantly extending the density range. We did establish a good data set of I-H thresholds at this condition. The upper limit of density clearly does increase with input power, but is rather robust.

Recent analysis, presented at TTF 2016, has focussed on trying to understand the reasons for this trend, looking at more local conditions. One possible explanation is that it depends on pedestal collisionality. For the same data set, it seems that for given pedestal pressure, I-H transitions occur at higher nu* (Figure 3). This might be consistent with the physical picture found in one earlier example with GPI, where it seems the GAM becomes weaker before the I-H transition (Figure 4, from [1]). One might expect the more relevant physical parameter for the GAM damping to be $\nu_{ii}$, which should scale quite similarly. Other observations, with reflectometry, indicate that the low frequency turbulence broadens in the period leading up to such transitions, becoming more L-mode-like before the transitions. Another possibility, less evident in the observations to date, is that the WCM amplitude becomes weaker. We propose to revisit such transitions to measure profiles, flows and turbulence more carefully, such that the underlying physics can be extracted, and with other parameters to see if the scaling of Figure 3 applies more

[Figures and graphs are not transcribed here but would be included in the actual document.]
generally. While GPI studies of I-H transitions were carried out in the 2015 campaign, these mainly used the low Bt range (~2.8 T) for which the power window is quite narrow and the same physics may not be controlling the I-H transition.

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.

We plan to start with LSN configuration and shape for which the high ne limit has been well documented, ie 5.8 T, 1.1 MA. We will document the details of the approach to I-H and H-mode as density is raised at two different power levels (eg 3.5 MW and 4.5 MW, adjusted depending on available power on the day. Shots will be repeated and puffs, gaps adjusted to get good GPI and ideally also CXRS data close to the transitions. Hopefully the same puffs can serve to raise ne and to provide good diagnostic data.

We will then repeat at a different current, 900 kA. This will

a) Give us information, presently lacking, about how the upper density limit for I-mode scales with Ip, q95.

b) Test the hypothesis of collisionality limit (does it hold in different conditions, and if so is it the same collisionality or collision frequency?).

A further test of the role of collisions will be to puff impurities and examine the change in power or local conditions at the I-H transition.

Time and RF power permitting, repeat at a higher plasma current, 1.3 MA. Will the upper density limit increase?
4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

Toroidal Field: 5.6-5.8 T, REVERSED
Plasma Current: 0.9-1.3 MA
Working Gas Species: D2
Density: Target nel 0.5-0.9e20 m⁻²
Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): Recent boronization is not essential but would be beneficial. Not the night before, though.
Equilibrium configuration (if possible, refer to database equilibria): Discharge 1120907028 or recent equivalent

4.2 Auxiliary Systems

ICRF Power, pulse length, phasing: Heating phasing, 80 MHz, variable power. Need D, E, J all operational, minimum 4 MW, 5 MW desired.
LHCD Power, pulse length, phasing: No
Pellet Injection (species): No
Impurity blow-off injection: Not needed. LBO may be permitted in some shots.
Diagnostic Neutral Beam: Desirable, not essential.
Special gas puffing: 8PSI D2 in the F-Port plenum for GP-CXRS. 8 PSI He in C-Port NINJA for GPI. Neon should be available, but we will avoid using except for controlled scans due to uncertainty in edge Z_eff. Argon for HIREX (some shots).
Cryopump: Desirable for ne control, and neutral pressure control. Not first shot; suggest N2 precool, He in reserve.
Non-axisymmetric Coils (Connections, Current): Standard reversed B configuration (for error field correction).

4.3 Diagnostics

List required diagnostics, and any special setup or configuration, e.g. non-standard digitization rate.

Essential: Edge and core TS, GPI, ECE, reflectometry to monitor fluctuation changes which signal L-I transitions, divertor and limiter thermocouples to check safe PFC temperatures.
Highly desirable: Edge CXRS, PCI, HIREX, inner divertor heat flux. Visible bremsstrahlung for Z_eff (ideally profiles).

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, extended run period – 10 hours maximum – etc.
1.5 run days. Order of steps, and division between run days, can be varied.

5.2 Shot sequence plan
For each run day, give detailed specification for proposed shot sequence: number of shots at each condition, specific parameters and auxiliary systems requirements, etc. Include contingency plans, if appropriate.

1. Unfuelled reference I-mode discharge. Load 1140625014, or recent equivalent. (5.8 T, 1.1 MA, stepped ICRF to 3.5 MW). Target nel ~ 7x10^19 m^-2. (to get ~9x10^19 m^-2 in the RF phase, or nebar 1.3-1.4). 2-3 discharges, to get one good case.

2. Fueling to reach I-H transition. Start with preprogrammed puff from NINJA, 10 psi D2 from inner valve to start (check pulses from eg 1140425024. If I-mode is maintained, increase puff. If neutral pressure is causing ICRF trips, turn on cryopump. 2-3 discharges.

3. Once upper limit to density/power/pressure is reached, repeat discharges with He puff for GPI, and puffs for CXRS. Need to document what is changing in local conditions, flows and turbulence that triggers the I-H transition. May be necessary to adjust gaps, which could imply shortening the high power duration and increasing the density ramp rate. Strike point sweeping may also be helpful to reduce tile heating and impurity influx. 4-6 discharges.

4. Repeat 2-3 at higher power (4.5 or 5 MW, as available). This should result in a higher density limit. (6 discharges)

5. Repeat one high power condition which gave steady I-mode, with Argon for Ti measurements. Once this data is obtained, do locked mode calibration shot. (2 discharges).

6. Reduce I_p to 900 kA. Establish I-mode, with target nel about 6e19 m^-2. At this lower current we should have enough ICRF to also reach I-H threshold at the initial density. (note: This I_p, B_t will give a q95 match to planned 7.8 T I-mode experiments at 1.2 MA; we will try to obtain L-I measurements with GPI for comparisons). 2 discharges.

7. Repeat fueling scans and documentation as in step 2, at a single power. Use our experience there to decide most effective valves and feedback methods, and needed gaps, so it should take fewer shots. Repeat discharges as needed to obtain full set of pedestal and fluctuation profiles (GPI, CXRS...) at this current, both in moderate density, maximum density I-modes, and at I-H transitions. We want to be able to assess physical variables, and ideally the mechanism, of the limit in density for I-mode. It is likely the absolute density limit will be lower, but possible the normalized density n_G will be higher. 4-6 discharges.
8. Again repeat a good I-mode condition, ideally without I-H, with Argon for HIREX and any other diagnostics needing a long steady window. Repeat locked mode shot if that is needed. (2 discharges).

9. Select one of above currents and powers, with robust I-mode window. Repeat with significant Neon seeding, to raise collision frequency for given $n_e$ and $T_e$. Will the density limit, and/or edge $T_e$ at transitions, change accordingly? 4 discharges.

10. Time and RF power permitting, repeat the sequence of steps 1-3 at 1.3 MA. 

As many discharges as we can

Total good discharges (28-34)

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.

- Improve the extrapolability of I-mode to ARC, ITER, JET DT, all of which would need to access I-mode at moderate density (for low L-I threshold power) and then increase it for high fusion power.
- Increase the physics understanding behind I-H transitions, and thus of both I-modes and H-modes.
- Contribute to Hubbard’s IAEA16 talk and NF paper, and future publications by Cziegler and others.

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