1. Purpose of Experiments

This experiment is intended to document the core particle transport in I-modes, as a function of collisionality, with other non-dimensional plasma parameters as fixed as possible. The goals include documenting the density peaking as a function of collisionality and the determination of transport coefficients (D,v). Doing so will bring added physical insight to the I-mode, and allow a comparison to conventional H-mode results obtained on other devices through similar experiments.

2. Background

This experimental proposal grew out of an ITPA joint experiment in H-modes, TC-15, the scope of which is the following: “collisionality scans will be performed in various devices in order to develop an understanding of the relationship between momentum and particle pinches, and to develop an understanding of the underlying physics by testing theoretical predications for pinches driven by low-k turbulence.” Concerning specifically particle transport, this is a joint ITPA experiment between JET, DIII-D and C-Mod where the main goal is to clarify the parametric dependencies of particle pinch on collisionality. This dependence must be known in order to make reliable extrapolations for the density peaking in ITER. Density peaking (and fueling needs in general) is currently one of the major open physics issues for the time being.
The momentum transport part has already been executed in JET, C-Mod, DIII-D, NSTX and AUG and therefore, the scope of this proposal is on the particle transport part.

![Figure 1. Multi-machine database on density peaking dependence on collisionality.](image)

Core particle transport and density peaking are one of the major unresolved issues in the area of tokamak physics when extrapolating to ITER from the present tokamaks. There are database studies reported earlier as shown in figure 1, but not many dedicated particle transport experiments. The multi-machine database work showed a very clear tendency that density peaking increases significantly when collisionality decreases [1].

A dedicated particle transport experiment in H-mode plasma with gas puff modulation to obtain the diffusion $D$ and convection $v_{\text{conv}}$ separately was executed in JET in 2014. Similar experiment was executed in DIII-D in 2012. The JET H-mode plasmas exhibit a strong dependence on collisionality $\nu^*$ as shown in figure 2 [2]. On the contrary, the collisionality scan on DIII-D did not show such a dependence, but rather no dependence [3]. The scanned factor in collisionality was 5 in JET, but only 2 on DIII-D and this may explain at least part of the contradiction. Also, what remains to be assessed is the role of source terms (both beam and neutrals from the edge) in contributing to the observed density peaking. The preliminary evidence from JET transport analysis suggests that the NBI fueling is maybe even dominantly responsible for the observed density peaking in JET.
C-Mod contrasts with the above devices, as the beam fuelling is negligible and the edge source will be varied with SOL opaqueness. Observations on Alcator C-Mod confirm and extend previous measurements from ASDEX Upgrade (AUG) and JET, where density peaking in H-mode was seen to increase as collisionality was lowered [4]. In the earlier work, peaking was also strongly correlated with $n_e/n_G$, the ratio of the plasma density to the density limit, and it was not possible to eliminate the latter parameter as the principal scaling variable. This led to divergent predictions for the density profile on ITER. The addition of C-Mod data allows the correlation to be broken, strengthening the case for collisionality as the controlling parameter. At the lowest collisionalities, C-Mod attained peaking factors $n_e(0)/n_d$ approaching 1.5 with $T_i = T_e$, high edge neutral opacity and no core fuelling. Taken together, data from the three devices strongly suggest that density peaking factor on ITER in ELMy H-modes will be in the range 1.4–1.6.
There are also some simulation results by Mikkelsen et al., on a null flux condition to match the particle transport and his conclusion is that there is some stabilization of ITG at the lower collisionality end of the scan and that the pinch is due to fluctuations at the higher end of the k scale [5].

Recently, there is evidence on ETG turbulence playing an important role in at least some C-Mod discharges [6]. The influence on momentum and particle channels is not yet clear.

In L-mode plasmas, the database work and dedicated JET experiment did not exhibit any density peaking dependence on collisionality. On C-Mod, the comparison between I-mode and L-mode particle transport is an interesting one – to see how similar or different D and v are under similar plasma conditions.

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 examination of particle transport, a collisionality scan with gas puff modulation will be the main experimental tool. The cleanest way to perform the collisionality scan is to keep mean density unchanged but vary the temperature in such a way that $\rho^*$, $\beta$ and $q$ are unchanged (called dimensionless collisionality scan). This means that the high collisionality end of the scan will have the lowest temperature, $B_t$ and $I_p$ and then during the scan, all these quantities will be increased to obtain lower collisionality points. This is most probably not possible to execute perfectly on C-Mod, but we will minimise the changes in other parameters as well as possible. The fine details of this method are described in the pulse plan.

The gas puff modulation must be small enough not perturb too much the background plasma. The analysis and interpretation is challenging if one cannot assume that the background plasma transport coefficients are time-independent to the perturbation, i.e. gas puff modulation itself. Thomson scattering is the key diagnostics to measure the response of the gas puff modulation.

This experiment will be run in I-mode. The main interest in TC-15 is in the core region at $0.2 < r/a < 0.8$ where the ITG turbulence is expected to dominate. On C-Mod, while there is not a steep density pedestal in I-mode, $n_{e0}/\langle n_e \rangle$ is similar to prior H-mode scalings which show increased peaking at low $\nu^*$ [7,8]. This is in fact consistent with core particle transport dominated by turbulence. We should compare both the local gradient lengths $R/L_n$ and global peaking factors.

The gas puff modulation has recently been tested in L-mode and shown to create an observable positive response in the density, both by interferometry and Thomson diagnostics, as illustrated in figure 3. In the L-mode shown, the plasma retains the additional particles for long times (>100ms). In order for multiple modulations of the gas puff to be possible, particle pumpout will need to be better in I-mode targets. This
remains to be tested in an ordinary I-mode target. During 1s of flattop I-mode time, between 5 and 10 modulation periods are possible. We should allow at least 50ms of gas on, 50ms off to get a noticeable response, but the final numbers will be determined by trial and error. The aim is to have the steady state density constant throughout the flat top. We will specify a mix of feedback (for mean nL04 control) and feed-forward for the modulation. We require the highest rep rate available on the C-Mod Thomson scattering system: 100Hz.

Initial shots would assess the viability of the gas puff modulation technique in I-mode, in concert with the quality of the available density diagnostics (Thomson, TCI, X-mode reflectometry). If these tests show that extraction of Ds and Vs is possible, then further shots to obtain specific I-mode parameters would be desired.
4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- Toroidal Field: 2.7T–7.9T (reversed field direction in I-mode)
- Plasma Current: 0.4MA–1.3MA
- Working Gas Species: D, H, He³
- Density: Line-integrated $n_{\text{io4}} \approx 0.5 \times 10^{20} \text{ m}^{-2} - 2 \times 10^{20} \text{ m}^{-2}$. Most of the shots will be run at around $n_{\text{io4}} \approx 1 \times 10^{20} \text{ m}^{-2}$
- Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): none
- Equilibrium configuration (if possible, refer to database equilibria): LSN imported from previous I-modes at each targeted Bt,

4.2 Auxiliary Systems

- ICRF Power, pulse length, phasing: up to 4MW, 80MHz heating phase, ~1s, H minority heating at 2.7T and 5.4T and He3 minority heating at 8T
- LHCD Power: None
- Impurity blow-off injection: Desirable not essential; CaF2 laser blow-off we will need to run this with the Ca crystal in HiReX-SR
- Diagnostic Neutral Beam: not needed
- Special gas puffing: Ar for rotation measurements, D, H and He3 for ICRH, D modulated
- Cryopump: yes
- Non-axisymmetric Coils (Connections, Current); Standard error correction configuration

4.3 Diagnostics

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

**Required:** ECE (except at low field), TS edge and core, Hirex Sr., divertor probes, Lyman alpha, TCI

**Desired diagnostics:** GPI, PCI, fluctuation reflectometry, profile reflectometry
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.

All I-mode shots will be in reversed field.

It is possible (maybe desirable) to test the gas puff modulation capabilities in piggyback on another I-mode experiment, before assigning dedicated run time. If we are unable to piggyback, then we will request a half-day to develop gas-puff modulation shots and begin the high- and mid-collisionality portion of the scan (5.4T and 2.7T cases). Based on the results, a second half-day will be requested to access the lower-collisionality portion (~7-8T).

Up to 1.5 total run days required.

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.

Part (1) (~5 shots):
Develop the gas puff modulation technique in I-mode, i.e. optimise the frequency and amplitude of the modulation in such a way that perturbation is large enough to be observable but small enough not to perturb the plasmas background. This pulse will also be the middle point in the 3-point collisionality scan. Therefore, use the parameters and profiles of the intermediate point in the collisionality scan at $B_t=5.4T$ and $I_p=1.0MA$ and $P_{in}≈3MW$ of input power. Line-integrated density at around $n_{l04}≈0.5x10^{20}m^{-2}$ (or as low as possible). We will try gas puff modulation using feed-forward on the main fueling valve (feedback off) by using a baseline feedforward (appropriate level to be determined) with a modulation on top of it. D(H) heating scheme to be exploited.

The above discharge becomes the basis for the middle collisionality point of the 3-point scan.

Part (2) (~5 shots):

**Collisionality scan, high collisionality point.** Run the high collisionality end of the collisionality scan at $B_t=2.7T$, $I_p=0.5MA$ and $P_{in}≈1MW$ and $n_{l04}≈0.5x10^{20}m^{-2}$ (or maximum that it can be at that field). Here $B_t$ can be higher if that turns out to be more stable, like 3.0T. The higher is the density for low field case, the better chances we have
so that other dimensionless parameters can be matched at higher field points within the scan. The higher field may also help to mitigate the effect of sawteeth (off-axis heating). Adjust $I_p$ and power accordingly. Goal is to have $T_e$ to be 2.8 times smaller (factor smaller if $B_t$ higher) than at $B_t=5.4T$ case. Apply the same gas puff modulation technique to create density modulation. D(H) heating scheme to be exploited.

**Part (3) (~5 shots):**

*3-point collisionality scan, middle collisionality point. This is the same type shot as in part 1.* Reload the target reference plasma at $B_t=5.4T$ and adjust input power to roughly match $\rho^*$ and $\beta$ in the low-field case. Apply the same gas puff modulation technique to create density modulation. Try to keep $n_{104}\approx0.5\times10^{20}m^{-2}$ or exactly what it was for the high collisionality shot in Part (2).

**Part (4) (> 5 shots):**

*Collisionality scan, low collisionality point. Run the low collisionality end of the collisionality scan at $B_t=7.9T$, $I_p=1.3MA$ and $P_{in}\approx5MW$ and $n_{104}\approx0.5\times10^{20}m^{-2}$ (or minimum that it can be at that field). $T_e$ should be 2.2 times larger than at $B_t=5.4T$ case. Here $B_t$ can be lower if that turns out to be more stable (and low density also easier achievable), somewhere above 7.0T that is operationally feasible. Adjust $I_p$ and power accordingly. Apply the same gas puff modulation technique to create density modulation. D(He$^3$) heating scheme to be exploited. Here the factor 2.2 in T increase may not be reached, but still matching as well as possible is an important aspect of this experiment.*

**Part (5) (~10 shots) [back-up]:**

If the dimensionless collisionality scan does not work out in points (3) and (4) above, the back-up plan is then run all the whole scan at 5.4T and then vary collisionality by varying temperature (by making a power scan) and possibly changing density but this of course will not keep $\rho^*$ and $\beta$ constant. Apply the gas puff modulation to all the shots here to get D and v.

### 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.

This experiment complements H-mode experiments run as part of the ITPA TC-15 joint experiment between JET, DIII-D and C-Mod. Similar experiments have been performed in H-mode on JET and DIII-D for L-mode and H-mode. I-mode data would be a unique contribution to extend the database to include new regimes and investigate the differences between L-mode and H-mode core transport. The role of fueling in determining the density peaking is not clear, dominant or not in JET, nor in DIII-D. This problem would be completely avoided on C-Mod.
7. References

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


