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

The purpose of this experiment is to vary the parameters which are thought to influence parallel impurity force balance responsible for the in/out impurity emissivity asymmetry seen on Alcator C-Mod. Mode-conversion flow drive, along with intrinsic rotation due to auxiliary heating will be used to scan the toroidal Mach number, $v_{i\phi}/v_{i\text{th}}$, over a range of $q_{95}$ and collisionality, $v_{ii}$.

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

An in/out poloidal asymmetry of the impurity density in the core plasmas has been observed on a ASDEX [1], ASDEX-U [2] and JET [3,4], where, predominantly, the low-field side (LFS) density is higher than on the high-field side (HFS) of the same flux-surface. In contrast to radial transport which, for most of the tokamak volume, is known to be much higher than neoclassical predictions, the parallel transport is accepted to be explained by neoclassical theory. For strong neutral beam-heating and massive, high-Z impurities, the toroidal rotation speed can be several times the impurity’s thermal velocity. In this regime, it is thought that centrifugal force sustains a pressure gradient along the field and the impurities accumulate on the LFS of a flux surface. Experiments on JET using Ni laser blow-off (LBO) have shown agreement with such theory in some cases [4], but not all [3]. In ASDEX-U, comparison of asymmetries for Ar- and Kr-seeded plasmas disagree with the mass scaling of such an asymmetry [2].

On Alcator C-Mod, an in/out asymmetry was first observed in H-mode plasmas by AXUV diodes measuring soft x-ray (SXR) and vacuum ultraviolet (VUV) radiation [5]. Figure 1 shows the emissivity profiles for an ELM-free H-mode and an ICRF-heated L-
mode, demonstrating both symmetry and asymmetry using the same diagnostic. These measurements where shown to not agree with theory that claimed centrifugal force was determining the parallel impurity force balance, Figure 2, despite large systematic errors in the measured rotation from x-ray crystal spectroscopy. More comprehensive theories of neoclassical parallel impurity transport [6] predict the in/out asymmetry for high-Z impurities to be a balance between ion-impurity friction pushing the impurities to the HFS of a flux surface and centrifugal force pushing to the LFS. Initial comparison for H-mode plasmas suggested the theory was still incomplete, but more detailed analysis is required. This theory predicts that the in/out density variation can be estimated by:

$$n_c = 2\epsilon \frac{M_o^2 - (1+\gamma)\Delta^2}{1 + (1+\gamma)^2 \Delta^2}$$

where $M_o \sim v_{z,q} / v_{th}$ and $\Delta \sim n_i Z^2 T_i^{3/2} B_T B_p^{-2} L_p^{-1}$. The term $\gamma$ is a ratio of density and temperature scale lengths.

More recently, an in/out asymmetry in AXUV emissivity has been observed in low $q_{95}$ plasmas with strong ICRF mode-conversion heating known to drive strong flows. Figure 3 shows the midplane emissivity measured by two different AXUV diode arrays in a $q_{95}=3.1$ (B$_T$=5.1 T, I$_p$=1.2 MA) plasma heated by 2.75 MW of D($^3$He) mode-conversion heating. A current scan done at fixed $P_{ICRF}$ and $<n_e>$ showed the asymmetry to increase with I$_p$ as shown in Figure 4. An in/out asymmetry has also been observed in low-$q_{95}$ I-mode plasmas. The hypothesis is that as the current is increased, $\Delta$ drops, allowing the centrifugal force to become a larger player in the force balance.

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.

Although in/out asymmetries have been observed more often in H-mode plasmas, the desire to scan a wide parameter space while probing with high-Z laser blow-off and maintaining steady-plasmas suggests that ICRF-heated L-modes (or I-modes) are a more attractive target. The laser blow-off system will be used to inject molybdenum into each RF pulse and the XTOMO and AXUV diode systems will measure the 2D variation of the emissivity. The increase in emission from molybdenum LBO is used to calculate the asymmetry due to Mo alone rather than estimate what level of it is is intrinsic radiation. HIREXSR will measure the rotation and ion temperature profiles using He-like and H-like Ar as well as measure the Ne-like molybdenum emissivity profile.

On-axis 50 MHz D($^3$He) MC and 80 MHz D(H) MH heating will be used at ~5.1 T and on-axis 78 MHz and 80 MHz D($^3$He) MC heating will be used at ~8.0 T. Due to the scaling of the mode-conversion flow drive (MCFD) in L-mode [7] ($I_p^{0.5}$ and $<n_e>^{0.9}$), a wide parameter space in $v_{z,q} / v_{th}$ and $\Delta$ can be covered by scanning current and line-averaged density at both toroidal fields. As $I_p$ is increased at fixed ICRF power, $M_o$ will increase as will $B_p$, reducing $\Delta$. As $n_l04$ is increased so is $\Delta$ and the change in rotation from MCFD decreases for a fixed amount of power, reducing $M_o$ down. Changes in the background temperature and scale length will be addressed using two different ICRF powers in the same shot.
4. Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- Toroidal Field: 5.1 T and 8.0 T
- Plasma Current: 0.7-1.6
- Working Gas Species: D2
- Density: 0.5 < nl04 < 1.1
- Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): no recent boronization
- Equilibrium configuration (if possible, refer to database equilibria): Unfavorable B drift direction for H-mode suppression. Can be run in either forward or reversed field. Start with equilibrium from 1091118010 or similar plasma.

4.2 Auxiliary Systems

- ICRF Power, pulse length, phasing: 2-4 MW 78/80 MHz (8.0 T) 2-4 MW 50/80 MHz (5.1 T)
- LHCD Power, pulse length, phasing: none
- Pellet Injection (species): none
- Impurity blow-off injection: yes, molybdenum
- Diagnostic Neutral Beam: desired for CXRS
- Special gas puffing: Ar for HIREXSR, 3He for MC heating
- Cryopump: yes (if USN)
- Non-axisymmetric Coils (Connections, Current): standard locked mode prevention
- Other:

4.3 Diagnostics

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

All electron temperature and density diagnostics (TS, TCI, GPC1, GPC2, FRCECE for 5.1 T). XTOMO and AXUV diodes for 2D radiation analysis. DNB-based CXRS for $T_i$ and $E_r$ but not GPI-based due to density control issues. XEUS and McPherson for impurity monitoring.

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 days broken into two ¾ days, one with J-ANT at 50 MHz, the other with J-ANT at 78 MHz. Note that MPXXX and MP610 could be used to fill in the remainder of the days.

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.
¾-day w/ J-ANT at 50 MHz

a) Standard locked-mode calibration shot for HIREXSR (1-2 shots)

b) ICRF-conditioning (1091118010) $I_p=1.1$ MA, $nI_0=0.9 \times 10^{20}$ m$^{-2}$ (2-3 shots)

2 MW of J-ANT from 0.6-1.0, 2 MW J-ANT + 2 MW D/E-ANT 1.0-1.4

LBO Mo injection at ~0.8 and ~1.2 seconds, adjust injection amount

c) Scan $I_p/nI_0$ parameter space bounded by MARFE, LM, limiter bloom and stability.

Adjust $^3$He puff as necessary. Collect targets near the following values. (~13-15 shots)

$I_p=0.7$ MA : $nI_0=0.5$
$I_p=0.9$ MA : $nI_0=0.5, 0.7$
$I_p=1.1$ MA : $nI_0=0.5, 0.7, 0.9$
$I_p=1.3$ MA : $nI_0=0.7, 0.9, 1.1$

d) Standard locked-mode calibration shot for HIREXSR (1-2 shots)

¾-day w/ J-ANT at 78 MHz

a) Standard locked-mode calibration shot for HIREXSR (1-2 shots)

b) ICRF-conditioning (1100210013) $I_p=1.3$ MA, $nI_0=0.9 \times 10^{20}$ m$^{-2}$ (2-3 shots)

2 MW of J-ANT from 0.6-1.0, 2 MW J-ANT + 2 MW D/E-ANT 1.0-1.4

LBO Mo injection at ~0.8 and ~1.2 seconds, adjust injection amount

c) Scan $I_p/nI_0$ parameter space bounded by MARFE, LM, limiter bloom and stability.

Adjust $^3$He puff as necessary. Collect targets near the following values. (~8-9 shots)

$I_p=1.0$ MA : $nI_0=0.6$
$I_p=1.3$ MA : $nI_0=0.6, 0.9$
$I_p=1.6$ MA : $nI_0=0.7, 1.0$

d) Standard locked-mode calibration shot for HIREXSR (1-2 shots)

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 from this experiment will be used to further understand the parallel impurity transport responsible for the in/out asymmetries in impurity radiation observed on C-Mod. It will be compared to neoclassical theories and be critical in the author’s PhD thesis work.

To understand the parallel transport, the radial ion temperature and flow profiles from HIREXSR are required. As this experiment will exploit mode-conversion flow drive, the physics of which is still under active investigation, the results from this experiment will extend that database.

The use of laser blow-off to inject impurities will allow these plasmas to be used to improve our understanding of radial transport by using HIREXSR and the XTOMO diagnostics to constrain molybdenum transport reconstructions. The goal of obtaining high Mach number would make these plasmas ideal for GYRO validation experiments where ExB shear is important.

The 8.0 T portion of these experiments has overlap with MP 610: “Investigate Thomson/ECE Discrepancy in High Temperature Discharges” and would add to that dataset.

February 3, 2011
7. References
Include references both to external and internal literature or communications which bear on this proposal. See Section 2.

FIGURE 1: First results demonstrating the in/out asymmetry in radiation in an ELM-Free H-mode in contrast to a symmetric distribution for an L-Mode plasma with significant molybdenum radiation.

FIGURE 2: Demonstration of the disagreement of the measured asymmetry scaling with theory using only centrifugal force.
FIGURE 3: Measurement of a substantial in/out asymmetry in an $q_{95}=3.1$ L-mode plasma with 2.75 MW of $D(3He)$ mode-conversion heating.

FIGURE 4: Scan of plasma current with fixed $n_e$ and $P_{ICRF}$ using $D(3He)$ mode-conversion heating. As $I_p$ is increased, so does the in/out asymmetry.