1. Purpose of Experiments

Examine lower toroidal field operation utilizing the 50 MHz ICRF and LH with higher $n_{\parallel}$. The toroidal field is expected to be in the range of 3.3 and 3.7 T where 50 MHz deposits very close to the axis for H-minority absorption at 3.3 T or at the LFS mid radius for H-mode/ITB production at 3.7 T. From calculations with TSC/LSC, the LH current driven maximizes at about $n_{\parallel} \approx 3.1$ at 3.3 T. A plasma current of 450 kA would be targeted. L-mode and H-mode regimes would also be tried, to establish LH operation at sufficiently low density (L-mode), and examine LH with H-modes.

Discharges at 2.7 T have been established for studying ITER-like scenarios with 2\textsuperscript{nd} harmonic H-minority, showing good heating efficiency, access to EDA H-mode, and higher $\beta_N$ (1110104). AT discharges were begun with ICRF at 3.4 T, showing higher $\beta_N$, higher pedestal temperature, and broader temperature profiles at $I_p = 450$ and 600 kA, compared to similar discharges at the standard field (1091117). Now with the availability of 1 MW of LH it of interest to try to establish AT scenarios with the possibility of ITBs at the lower toroidal fields.

Background

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

We are utilizing the flexibility of the 4 strap ICRF antenna at J-port to operate at 50 MHz which allows on-axis heating in H-minority at a toroidal field of about 3.3 T. In addition, the spectrum flexibility of the LH system allows $n_{\parallel}$ peak spectra over the range of 1.5 to 3.0. The reduction of the toroidal field from the standard operating point of 5.4 T to 3.3 T provides an increase in $\beta_N$ by a factor of 1.65. The bootstrap current fraction is
unchanged since it is independent of $B_T$, and ideally one can produce the same $f_{BS}$ at 3.3 T as is produced at 5.4 T, but with different $\beta_N$ and $q_{95}$. For the situation with $B_T = 3.3$ and 3.7 T, the ICRF power available will be only that from J-port, ~2.5 MW. The precise dependence of the LH power available as a function of $n_\|_i$ is unclear, although reflected power appears to increase at the higher $n_\|_i$ and directivity may be degraded. Shown below are some simulations from TSC/LSC to show the LHCD at higher $n_\|_i$ and a toroidal field of 3.3 T. These simulations represent optimistic projections to higher power ($P_{LH} = 2.5$ MW), but were the closest simulations at hand to perform quickly. The profiles of the LH and total currents driven are shown, as well as the electron temperature and density used. These are not intended to predict the results for these experiments, but show LHCD at the lower field, and the need to shift to higher $n_\|_i$ to compensate the reduction in toroidal field.

The purpose of this experiment is to begin the exploration at lower $B_T$ operation to identify 1) if LHCD can be established, and 2) if LH can be combined with ICRF in L-mode, H-mode and H-mode/ITB plasmas. If successful, this would provide the basis for higher betaN operation at $q_{95}$ values expected for ITER steady state scenarios.

Shown below in Fig. 2 is the accessible density versus $n_\|_i$ for varying toroidal field, showing that at $B = 3.3$ T, $n_\|_i$ needs to be > 2.5 for $n > 1e20$. For discharges with $I_p = 450$ kA, in figs. 3 and 4 below are plots from G. Wallace’s widgit showing the local accessibility for the same L-mode densities of $n_{L0} \sim 5.5e19$ at $B = 3.3$ (1091117028) and 5.4 T (1080118001) to show the shift in accessible $n_\|_i$ strictly from the reduction in toroidal field. The launched $n_\|_i$ is at the right. Below these graphs, in figs. 5 and 6 are the same diagram for H-modes with the same densities, $n_{L0} \sim 0.9e20$ at 3.3 (1091117032) and 5.4 T (1080118014). These cases should suffer from the nebar limit of 1e20 /m$^3$, but we will attempt inboard wall plasmas if necessary. Finally in fig. 7, the same accessibility diagram is shown with a H-mode/ITB plasma at 5.4 T (1080516021), running this at 3.3 T would require a higher $n_\|_i$ than indicated here, like the other comparisons. The increase in $n_\|_i$ for accessibility to compensate the toroidal field change is about 0.8, while that to compensate the density from $n_{L0} = 3.5$ to 6, is about 0.3.
Figure 1. TSC/LSC simulation of LHCD in C-Mod at 3.3 T using H-mode density, showing the need to shift to higher $n_{||}$ to maximize $A/W$.

Figure 2. Accessible $n$ versus $n_{||}$ as a function of toroidal field.
Figure 3. L-mode plasma at 3.3 T with $n_l04 = 0.55e20$

Figure 4. L-mode plasma at 5.4 T with $n_l04 = 0.55e19$

Figure 5. H-mode plasma at 3.3 T with $n_l04 = 0.9e20$
2. 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.

LH only will be injected into low density L-modes, and both a density and a phase scan will be done to find the strongest LH impact on the plasma. The highest workable phase will then be used to combine LH with the higher density H-modes or H-mode/ITBs. This sequence would be done at the low plasma current of 450 kA in order to maximize the LHCD and reduce the H-mode density, and at the toroidal fields of 3.3 and 3.7 T. The MSE diagnostic, loop voltage, li, fast electron signature will be tracked to understand the impact of the of the heating/CD sources at the lower field. ITBs will also be examined based on (1080516) where LFS mid radius ICRF injection created H-modes with density peaking that did not require on-axis stabilization.

\( B_T = 3.3 \text{ T} \quad 50 \text{ MHz } @ \text{ R} = 0.67 \text{ m} \)

Higher field should allow better LH, and allow ITB formation
\[ B_T = 3.7 \, \text{T} \quad \text{50 MHz @ } R = 0.77 \, \text{m (mid radius, LFS, ITB)} \]

We must be prepared for the LH density limitation at nebar ~ 10^{20} / m^3, requiring moving the plasma very close to the inboard wall for H-modes, will need to optimize to find maximum distance that avoids this limit. It appears that L-mode can avoid this limit since the density can be controlled in this regime.

### 3. Resources

#### 4.1 Machine and Plasma Parameters

Give values or range for:

- Toroidal Field: \[ 3.3 \, \text{T}, 3.7 \, \text{T} \]
- Plasma Current: \[ 0.450 \, \text{MA} \]
- Density: Target 5e19 m^{-3}, variable (cryopump not precluded).
- Equilibrium configuration (if possible, refer to database equilibria): shot 109117032, then adjust Ip ramp rate

#### 4.2 Auxiliary Systems

- ICRF Power, pulse length, phasing: 50 MHz, J-port essential, maximum power; D&E at 80 MHz (2\textsuperscript{nd} H-minority)
- LHCD Power, pulse length, phasing: 0.5-1.0 MW or maximum power, variable phase \( n_\parallel = 2.7-3.1 \), longest pulse available.
- Pellet Injection (species): no
- Impurity blow-off injection: no
- Diagnostic Neutral Beam: Highly desirable
- Special gas puffing: NINJA (with D2) should be available.
- Non-axisymmetric Coils (Connections, Current): Yes; optimized to reduce locked modes.

#### 4.3 Diagnostics

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

Essential: Thomson, Magnetics, Hard x-rays, ECE (gratings?), TCI, HIREX, probes in LH grill.
Desirable: MSE, CXRS, SOL probes.

### 4. 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.
The toroidal field would be 3.3 T in the first phase, 3.7 T in the second phase. All plasmas will be 450 kA. LH into L-modes, and then progressively move H-modes or H-mode/ITBs into LH phase with ICRF.

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) Recover 1091117032, \(B_T = 3.3\) T, no ICRF, \(n_{l04} \sim 4e19\) at end of Ip ramp, L-mode for LH pulse
   a. Adjust Ip rampup time to 350 ms
   b. Inject LH from 100-600 ms, \(n ||\) scan from 2.5, 2.7, 2.9 (or 3.0)
   c. Adjust density at end of ramp from \(n_{l04} \sim 3e19 - 7e19\)
   d. Add ICRF at 650 ms, 1.0-2.5 MW (1.0 MW with slow rise in flattop) to make EDA H-mode
   e. Using highest reliable \(n ||\) move ICRF on time progressively earlier, moving H-mode into LH pulse (\(n_{l04} > 4.5-5e19\) should trigger H-mode)
   f. Prepare to examine close-to-inboard-wall operation to avoid density limit for LH

2) Shift to higher \(B_T = 3.7\) T to examine ITB with LH, \(n_{l04} \sim 4e19\) at end of Ip ramp, L-mode for LH pulse
   a. Adjust Ip rampup time to 350 ms
   b. Inject LH from 100-600 ms, \(n ||\) scan from 2.5, 2.7, 2.9 (or 3.0)
   c. Adjust density at end of ramp from \(n_{l04} \sim 3e19 - 7e19\)
   d. Add ICRF at 650 ms, 1.0-2.5 MW (1.0 MW with slow rise in flattop) to make EDA H-mode/ITB
   e. Using highest reliable \(n ||\) move ICRF on time progressively earlier, moving H-mode into LH pulse (\(n_{l04} > 4.5-5e19\) should trigger H-mode)
   f. Prepare to examine close-to-inboard-wall operation to avoid density limit for LH

5. 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, or an external database.

The experiments will explore the feasibility of LH and ICRF operation at the lower field, providing information for modeling of discharges when more power is available.

6. References
Include references both to external and internal literature or communications which bear on this proposal. See Section 2. MP585 Low Bt Discharge Development with 50 MHz (11/23/2009)
MP522 Slow Ip ramps with Low Ip at 450 kA, LH and ICRF (2/25/2008)
MP454 Low Ip H+ITB plasmas, modulation and LH injection (5/19/2008)
APS 2008, Progress Using LHCD and ICRF on Advanced Tokamak Discharges on Alcator C-Mod (poster)