**1. Purpose of Experiments**

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

This MP will follow up on MP 612 by G. Wallace et al., “Expanded exploration of LHCD Density Limit”, beginning an assessment of LHCD in high $T_e$ high confinement regimes which are most relevant for advanced scenarios. This will provide important benchmarking of LH models, and an assessment of which scenarios may be realistically explored in future scenarios experiments.

**2. Background**

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

As discussed in the Wallace MP, LHCD efficiency – or at least non-thermal signatures – fall off unexpectedly rapidly as density is increased above about $n_{e\text{bar}} = 10^{20} \text{ m}^{-3}$ [1,2]. If found to be a hard and universal “density limit” this would be a serious limitation for advanced scenarios using LHCD on C-Mod and other experiments, since most high confinement plasmas (in particular all C-Mod H-modes) have higher densities. Modelling using modified GENRAY with CQL3D indicates results can be explained by collisional damping in the SOL. Cesario proposes edge parametric decay as an explanation for similar results on FTU [3]. For either of these physical mechanisms, a key variable to increase core LH absorption and current drive efficiency is plasma temperature. Indeed, significant increases in LHCD were observed on FTU when edge $T_e$ (both inside and outside LCFS) was increased by means of lithium conditioning. Higher core $T_e$ would increase single-pass absorption, reducing the number of passes of rays through the SOL. Higher SOL $T_e$ would reduce the damping by either collisions or PDI. Fortunately, high $T_e$ is also the fusion-relevant condition for scenarios which combine LHCD with ICRF, and achieve significant bootstrap fraction. Increased $T_e$ may
be the best (only?) hope for achieving significant LHCD on C-Mod above \(10^{20} \text{ m}^{-3}\), so it is important we begin exploring this possibility as early as feasible.

Most of the LH experiments on C-Mod to date, and in particular all of the high \(n_c\) ramp experiments, were conducted in ohmic targets with strong gas puffing and cold plasmas; for the lower \(N_{\parallel}\) cases where LH efficiency should be highest, we were usually in a low single pass regime. There is thus significant potential for improving LH absorption by increasing \(T_c\) in the confined plasma, by combining with ICRH and exploiting improved confinement regimes (I-mode in addition to L and H-modes). We do not have such direct control over SOL \(T_e\) profiles, which are constrained by power balance (see LaBombard MPs 570 and 591 in progress as part of 2010 Joint Milestone). However, some variation is expected to occur in conjunction with scans of power and configuration. Some limited modeling of possible scenarios has been carried out by Randy Wilson [4]. Uncertainties in expected parameters, particularly 2-D SOL profiles, are such that experiments are urgently required. The results will both serve to benchmark LH models, GENRAY-CQL3D as well as potentially EU codes, and will provide a reality check on expectations for LHCD in possible C-Mod advanced scenarios. (For example, can we use H-modes or are we restricted to L or I-modes?) They will contribute strongly to ITPA joint experiment ITPA IOS 5.3 (high \(n_c\) LHCD), with similar experiments performed on JET, Tore Supra, and FTU.

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.

The primary knob to control \(T_e\) will be ICRF power. We plan two main parts to the run plan. The first scan will be in USN, going from ohmic to L-mode to I-mode. This should dramatically increase \(T_e\) without a large change in density, though we must expect some variation simply due to RF fuelling. Parameters will be selected to give I-mode access with the RF power available (E-port and J-port only, due to LH interaction issues) and at a density in the range where xray emissivity typically decreases (\(n_{\text{bar}} \sim 1.2 \times 10^{20}\) seems reasonable for both obtaining I-mode, though it is on the low end of the range to date, and potentially observing LHCD).

A second scan will be in LSN, going from L-mode to H-mode. Here we will reduce target density and current so as to give H-mode densities as close as possible to the non-linear range. While core densities will be considerably higher, they will fall off more rapidly in the SOL which may be advantageous for LH penetration. This scan should allow some comparison of LH efficiency in H-mode, with steep \(n_c\) profiles and scrape-off lengths, at densities approaching prior ohmic, L and I-mode experiments. While not the primary purpose of this MP (and in fact a potential complication in analysis), pedestal modification via LHCD is likely in these discharges. Impurity radiation may be used to decrease this.

If MP 619 has shown promising differences in ohmic discharges with double null, where shorter scrape-off-lengths are expected, we will also explore ICRH in this configuration,
possibly with inner wall puffing. Wilson’s modeling has shown that some of the wave damping can occur in the HFS SOL, and is reduced as these profiles are steepened.

For all of these conditions, non-thermal signatures (x-rays, ECE) will be key diagnostics for model validation and direct and indirect measures of current profile changes (loop voltage and li, plus MSE and polarimeter if at all feasible) will be very important.

Resources

4.1 Machine and Plasma Parameters

Give values or range for:

- Toroidal Field: 5.4-5.7 T
- Plasma Current: 600-1100 kA
- Working Gas Species: D
- Density: nebar=0.5-1.5x10^{20} m^{-3}
- Boronization Requested (if yes, specify whether overnight or between-shot, how recently needed, and any special conditions.): Recently boronized, but not the night before to allow good density control.
- Equilibrium configuration (if possible, refer to database equilibria): 1100915027, slightly reducing Ip and nel.

4.2 Auxiliary Systems

- ICRF Power, pulse length, phasing: J- and E-port, up to 4 MW, 0.7 s, heating phasing
- LHCD Power, pulse length, phasing: 750 kW- 1 MW, 0.5 s, 75°, 90°, 110°, 125°
- Pellet Injection (species): N
- Impurity blow-off injection: N
- Diagnostic Neutral Beam: Y
- Special gas puffing: N, Ne or Argon puffing in some shots.
- Cryopump: YES, all discharges to control ne.
- Other:

4.3 Diagnostics

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

Required: Feedback systems (TCI, magnetics), edge and core TS, divertor Langmuir probes, HXR, thermal and non-thermal ECE (at 5.4 T), microwave spectrum analyzer, LH video camera, MSE highly desired (unless unavailable for campaign).

Desirable: ASP, FSP, WASP, X- and O-mode reflectometers, divertor and limiter thermocouples, polarimeter.

4. Experimental Plan

Both sections must be filled in.

July 23, 2010
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.

2 run days, with order of parts, and second day, contingent on results obtained.

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.

Parameter details and subject to modification depending on prior LH results in MP 619.

Day 1, Part A: USN power scan, at single condition
1. Ohmic USN target: 5.4 T, 1.1 MA, 110° phasing (est \( n_{\|} = 2.3 \), \( P_{LH} = 0.8-1.0 \) MW (set power to highest value to which LH2 has been reliably conditioned, and \( n_{\|} \) to a value just above accessibility limit in measured profile), \( n_{e} = 1.2 \times 10^{20} \) m\(^{-3} \). Shape from 1090915027. (1-2 shots; expect little LHCD or xray emission)

2. ICRF power scan (L and I-mode). Add ICRH, from beginning of flat top (0.5-1.5 s). Add LHCD later, 0.7-1.2 s, same power as in step 1. ICRF powers 1 MW, 2 MW, 3 MW, 3.5 MW (adjust last steps, and LH timing according to available E and J power, and observed L-I (and H-mode) threshold. Expect L-I threshold at this \( I_{p} \) to be about 4-5 MW loss power, or 3-4 MW RF power. If no I-modes, consider decreasing \( I_{p} \). 10 shots.

Look for increases in non-thermal signatures, and \( V_{\text{loop}} \) drops, as ICRF power increases, and in particular as edge \( T_{e} \) rises in I-mode. Once signatures are seen, repeat shots as needed to get good MSE data near LH turnon.

If, as we hope, positive trends are seen in the high \( T_{e} \) I-mode or L-mode USN plasmas, then go to part B where plasma and LH parameters are scanned to broaden the data set and indicate the directions to optimize LHCD. If not, go directly to Part C, H-mode/LSN configuration.

Part B: Parameter scan in USN L and I-mode
1. \( n_{\|} \) scan in I-mode. Vary LH phasing and \( n_{\|} \) in highest \( T_{e} \) L or I-modes obtained above, to find the optimum efficiency (expected to be just above accessible limit, but this need to be checked.). Start with 3 values per discharge, observe x-rays and ECE. Repeat at optimal value to for MSE. 4 shots.

2. Reduce density. First, reduce average target density to 1.0 or 1.1 \( \times 10^{20} \) m\(^{-3} \). Repeat power scan, trying to get I-mode and high \( T_{e} \). Keep adding LHCD in steady phase as in A.2 (note this is below the prior range of I-modes at this current, if need be drop to 0.9 or 1.0 MA, which would also decrease the L-I threshold). 6 shots.
3. Raise density. Increase average target density to $1.5 \times 10^{20} \text{ m}^{-3}$ (more typical of prior I-modes). Repeat power scans with LHCD, varying $N_\parallel$ within shot if signatures are lost (optimal value likely to increase). Are non-thermals and current drive still seen? If so, increase further to find out the limit, and magnitude of effects. **6 shots.**

**Part C: H-mode power scan**

For this part, realize there will be large density differences between L and H-mode, hence start with a lower current and density ohmic target to get minimum density in H-mode; plan to use highest $n_e$ ohmic discharges from MP 619 for an approximate comparison.

1. Optimize low density H-mode target. 600 kA, ohmic nel $6 \times 10^{19} \text{ m}^{-2}$, cryopump on. 2.5 MW ICRF. Start with $S_{Sep} -5 \text{ mm}$, try sweeping up to slightly USN after H-mode is formed to minimize density. Ref shot 1080306013, or one from Hughes new MP if that is run first; these MPs are complementary and can be in either order. **2-4 shots**

2. Add LHCD, after H-mode is steady. Observe non-thermal signatures. **2 shots**

3. If as is possible the LHCD is having a large effect on $n_{ped}$, $T_{ped}$, try N puffing to minimize this complicating effect on $V_{loop}$ etc, hopefully without cooling the pedestal too much. The tradeoff is that $n_e$ will be higher (perhaps 2.0 vs $1.6 \times 10^{20} \text{ m}^{-3}$) and LH effects will then be lower. **2 shots**

4. ICRF power scan. 1.5, 3.0, 3.5 MW. Should vary $T_{ped}$, with little effect on $n_e$ profiles. Continue adding LH power into established H-modes, look for current drive and non-thermal signatures. Repeat shots if needed for MSE. **6-8 shots.**

**Part D: Double null configuration**

Part of MP 619 will explore LHCD in double null ohmic discharges. If these experiments have shown differences between DN and LSN, USN discharges – which presumably would be due to the different SOL profiles - then we will also perform an ICRF power scan into DN discharges. There is much less experience with confinement in this configuration – either L or H-modes, or possibly I-modes, will be obtained depending on power (expected LH threshold 1.5-2x LSN level).

1. Set up double null discharge, 1.1 MA, nebar $1.2 \times 10^{20} \text{ m}^{-3}$ as in A.1. LHCD into flat top. **2 shots.**

2. Scan ICRF power shot to shot, 1 MW, 2 MW, 3 MW. Add LHCD into steady heated period. **6 shots.**
3. If non-thermal signatures are seen, and increase with $T_e$, then scan $N/I$ to optimize. 3 shots.

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, an ITER request, or an external database.

Results from these experiments will be included in the IAEA presentation of Greg Wallace and possibly the APS invited talk of Andrea Schmidt. Further investigation of the LHCD density limit was identified by the PAC, and the C-Mod team, as a top priority research area for the 2010 and 2011 campaigns. These experiments will contribute to the ITPA IOS 5.3 (high $n_e$ LHCD, led by Hubbard), and results would be presented at the October 2010 IOS meeting. They will help to validate and improve LHCD models, which will then be used for ITER predictions, to be presented by G. Wallace in APS ITER session. They will be critical to informing the feasibility and optimization of later experiments in the Advanced Scenarios thrust (eg, hybrid scenario (H-mode) and LHCD into higher bootstrap current I-modes).

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

4. J.R. Wilson, APS poster 2009.