Progress Using LHCD and ICRF on Advanced Tokamak Discharges on Alcator C-Mod

C. E. Kessel¹, A. E. Hubbard², P. Bonoli², Y. Lin², R. Parker², A. E. Schmidt², S. Scott¹, S. Shiraiwa, A. C. C. Sips³, G. Wallace², R. Wilson¹, S. Wolfe², S. Wukitch², and the C-Mod Team

¹Princeton Plasma Physics Laboratory
²Plasma Science and Fusion Center, MIT
³Max Planck IPP, Garching

APS Division of Plasma Physics, November 2008
Abstract

PP6: 74  Advanced tokamak discharges on Alcator C-Mod are targeting high non-inductive current fraction with bootstrap and lower hybrid (LH) current drive, and high confinement from ICRF heated H-modes. Plasma currents in the range of 450-600 kA are coupled with up to 3.5 MW of ICRF and 0.6-0.9 MW of LH. Longer plasma current rampup times are used to allow the ICRF and LH to modify the current profile. Delay of the sawtooth onset is significant using the LH by itself and in combination with the ICRF. ICRF H-modes in the rampup show they are not as effective at delaying the sawtooth as LH. Time dependent simulations of the discharges with the TSC and LSC code (ray-tracing with 1D FP) have helped to determine the magnitude of the LHCD and the resulting effects on the safety factor profile. Analysis with GENRAY-CQL3D (ray-tracing with 2D FP) will be given.

Work supported by USDoE DE-AC02-76CH03073, DE-FC02-99ER54512.
Exploring the Impact of ICRF and LHCD on the q/j-profile in Alcator C-Mod

- **Lower Hybrid** current drive provides a strong source of non-inductive current at large minor radius (far off-axis), and 100% electron heating
- **ICRF** provides central heating, assume approximately 50% electron and 50% ions

- Long term goal is to produce 100% non-inductive plasma current with LHCD and bootstrap current
- Near term goal is to elevate the safety factor and control the q-profile evolution in the Ip rampup and flattop.
- Control variables investigated to date include:
  - Divert time/heating time
  - H-mode onset time
  - Density control to optimize LHCD and H-mode onset
  - Timing of ICRF heating and LH heating/CD
2007 Campaign Focused on $I_p = 600 \text{ kA}$

ICRF power (2.4 MW) in L-mode rampup provides little or no delay of sawtooth onset, for both 500 and 1000 ms rampup.

LH power (0.4 MW) only in L-mode delays sawteeth onset by 150 ms.

Combination of ICRF (2.4 MW) and LH (0.4 MW) in L-mode delayed sawteeth onset by
- 175 ms for 500 ms rampup
- 375 ms for 1000 ms rampup

Simulations indicated that, in contrast to larger tokamaks, slower $I_p$ ramps are only effective at modifying $q(0)$ with early heating/CD or H-mode onset.
2008 Campaign Focused on $I_p = 450$ kA

Establish H-mode onset in $I_p$ rampup with ICRF power -> examine sawtooth onset

Establish LH only impact on sawtooth onset

Examine the combination of LH and ICRF induced H-mode
ICRF Injection in Rampup and H-mode
Timing ICRF H-mode Onset in Rampup Controls Drop in li(1)

H-mode onset time

ICRF at 200 ms
H-mode at 250 ms
ICRF at 350 ms
H-mode at 400 ms
ohmic
Sawteeth are Delayed Longest by Earliest H-mode Onset

sawtooth onset time

ICRF at 200 ms
H-mode at 250 ms
ICRF at 350 ms
H-mode at 400 ms

early H-mode
late H-mode
ohmic

ECE central Te, keV
Without an H-mode, ICRF Power Does Not Affect $\text{l}_i(1)$

- Graphs showing $I_p$, $\text{l}_i(1)$, $n_{el}/m_2$, and $P(\text{ICRF})$, with labels indicating ICRF H-mode, ICRF L-mode, and ohmic.
Without an H-mode There is No Sawtooth Onset Delay
ICRF Heated High Density H-mode gives Strong Decrease in $\text{i}_1(1)$ vs L-mode

H-mode onset time

But, there was little difference in sawtooth delay between high density L-mode and Ohmic (both $\sim$175 ms)
Little Difference Between High Density L-mode and Ohmic for Sawtooth Delay

ICRF H-mode

ICRF L-mode, high n

ohmic

ECE Central Te, keV
Lower Density ICRF L-mode Does Have Lower \( l_i(1) \) Than High Density ICRF L-mode, low \( n \)

ICRF L-mode, high \( n \)

Again, no difference in sawtooth delay between these cases (both \( \sim 175 \) ms)
Sawtooth Onset is Unaffected by High or Low Density in ICRF L-modes

ICRF L-mode, low n
ICRF L-mode, high n

ECE Central Te, keV
Summary - ICRF Heated Only

- Using 500 ms rampup time to Ip = 450 kA

- Inducing H-mode in the rampup can
  - Lower li(1) from 1.6 to 1.45 at end of ramp over ohmic
  - Delay the sawtooth onset from 100-200 ms over ohmic

- The earlier the H-mode, the more pronounced the delay in sawteeth, while li(1) relaxed to similar values by the end of the ramp

- Similar ICRF power with L-mode does not reduce li(1) and does not delay sawteeth

- Low or high density ICRF L-modes show weak differences in li(1) and sawtooth onset

- Density control is found to be critical for “on-demand” access to ICRF H-modes – raising density above ‘low ne limit’ for L-H gives H-modes.
LH Injection in $I_p$ Rampup
With LH injection, $li(1)$ is Progressively Lower in Rampup as Density is Lowered

- LH L-mode, low $n$
- LH L-mode, med $n$
- LH L-mode, high $n$
- ohmic
Sawtooth Onset is Delayed by Up to 500 ms with LH, as Density is Lowered

LH L-mode, low n
LH L-mode, med n
LH L-mode, high n
ohmic
End of LH pulse
Addition of Low Power ICRF Makes No Change to $\text{l}_i(1)$ Compared to LH only

LH L-mode, low $n$
LH L-mode, low $n$, 1 MW ICRF

$\text{l}_i(1)$

P(ICRF), MW

P(LH), kW

nel, /m²
Low ICRF Power Added to LH Shows Only Minor Change to Sawtooth Delay
ICRF Injection in Rampup with H-modes In Combination with LH
Producing ICRF H-modes in Ramp More Difficult Than Using LH to Reduce $li(1)$

- LH, L-mode, med n
- LH with ICRF on at 200 ms
  - H-mode at 400 ms
- LH
  - ICRF on at 350 ms
  - H-mode at 350 ms
- LH
  - ICRF on at 500 ms
  - H-mode at 700 ms
Presence of High ICRF Power and H-modes Only Weak Effect on Sawtooth Delay Compared to LH Only
Radiated Power Increases with ICRF, and Influences H-mode Quality and Timing

LH only results in low radiated power

LH, L-mode, med n
LH with ICRF on at 200 ms
H-mode at 400 ms

LH
ICRF on at 350 ms
H-mode at 350 ms

LH
ICRF on at 500 ms
H-mode at 700 ms
Summary - LH and ICRF

• LH power is effective at lowering li(1) and delaying sawteeth in L-mode current rampup
  – Effect is amplified by reducing density, or presumably by raising power at fixed density
  – At low density sawtooth delayed by 500 ms to the end of LH pulse

• Addition of low ICRF power (≈ 1 MW) to LH in L-mode rampup makes no difference to effects on li(1) or sawtooth onset

• High power ICRF H-modes were generated at different times in rampup and after rampup, along with LH
  – H-mode provides a strong reduction in li(1)
  – However, H-modes and their timing were unreliable due to radiated power from high Z

• A combination of LH at lower density in rampup, with ICRF H-mode and higher density in flattop can provide a strong li(1) reduction and elevation of q(0)
Higher LH Power
Modification to H-mode Evolution
Clear delay of sawteeth activity with 0.8MW LHCD

- Slow ramp to 600kA

- With LH, delay of sawteeth until 0.511 s,
- Without, sawteeth start at 0.257s

- 800kW LH, reliably

- Modest density increase with LH
- \( I_i \) lower with LHCD

- In at least one LH shot (e.g., 1080414018), sawteeth started earlier but stayed very small, indicating \( q(r) \) was modified.
High heating power phase was scanned in time (0.3s-0.7s), peak $W$ varied.

- Peak stored energy varied depending on ICRH (H-mode) timing with respect to $q_0=1$.
- Best performance H-modes were produced when H-mode triggered close to sawtooth onset time. Qualitatively similar to “hybrid” or “improved H-mode” results on AUG and JET.

Oral JO3:06, Hubbard et al
The most consistent difference between discharges modified by LHCD and those without is in L-H transitions

- With ohmic, sawtoothing targets, L-H transitions within ~ 20 ms (about $\tau_E$) of ICRH.
  - Expected since $P_{ICRF} \sim 3 \times P_{thresh}$.
  - Transition is very hard to distinguish on $D_\alpha$, $dn/dt$ etc. Do see a drop in magnetic fluctuations.

- In LH-modified (small or no sawtooth) discharges, L-H transition is delayed, occurs 60-70 ms after ICRF.
  - Clear $D_\alpha$ drop, break in slope of $n_e$ jump in edge $T$, etc.
  - Slower density rise after transition.
  - Generally higher peak $T_{edge}$ in the H-mode which correlates (as usual) with higher peak stored energy.
Summary – High power LHCD transiently improves following H-modes

- LHCD in current ramp successfully stabilized, or in some cases reduced, sawteeth in 600 kA discharges (also in the one 800 kA, $q_{95} \sim 4$ discharge tried)
- ICRH was added to these targets to make H-modes. In many (though not all) cases the stored energy was transiently higher.
- In the “LH modified” discharges, the L-H transition is delayed (70 ms vs 20 ms after ICRH turn-on) and is much more distinct. Density rise is slower.
- Higher stored energy in these H-modes is correlated with higher edge temperature (profile ‘stiffness’).
- Initial analysis with TRANSP+LSC shows maximum LHCD $\sim 70$ kA, decreasing and shifting further off-axis when ICRH turns on (presumably due to changes in $n$, $T$).
- Other comparisons show that LSC typically underpredicts current drive by $\sim 60\%$, vs CQL3D code. (Bonoli, ITPA 2008). Future work will include QCL3D modelling of this case. *Is the change in $j(r)$ responsible for differences in L-H transition and pedestal?*
Key Results

• LHCD in current rise is by far the most effective means of changing current profile on C-Mod, and delaying sawteeth, in some cases by 500 ms (to the end of LH pulse).
• ICRH in L-modes is ineffective at reducing \( I_i \) or delaying \( q=1 \), often in fact gives earlier sawtooth onset.
• Inducing H-modes in the current ramp does reduce \( I_i \), and gives modest (100-200 ms) sawtooth delay. Controlling density (above or below ‘low \( n_e \) limit’) provides a reliable means of triggering or avoiding H-modes.
  – However, impurities and radiation increase with high power ICRH affecting H-modes and discharge reproducibility.
• Experiments using LHCD to modify \( j(r) \), and ICRH to trigger H-modes in flat top, showed transient improvements in H-mode performance, similar to “hybrid” scenario elsewhere.
  – Apparently related to delayed L-H transition, higher T pedestal.