Progress and Prospects of Advanced Integrated Scenarios on Alcator C-Mod


MIT Plasma Science and Fusion Center
*Princeton Plasma Physics Laboratory

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ABSTRACT

“Advanced” scenarios, with a high non-inductive current and greater degree of control over current and pressure profiles, offer significant potential advantages over conventional tokamak operation. Key issues for application to burning plasmas such as ITER, and for DEMO, include obtaining improved confinement with low external torque and particle sources, and with coupled electrons and ions. External current drive in high confinement plasmas with an edge transport barrier, and compatibility with high divertor heat fluxes, are also important. The Alcator C-Mod integrated scenarios program focuses on addressing these challenges. Key new tools include a lower hybrid current drive system for current profile control and a cryopump for density control. Promising results from recent experiments using both of these will be reported. Modeling shows that scenarios with high non-inductive current fraction are achievable, with increased LHCD power.

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General aims of “Advanced Integrated Scenarios”

- Advanced Scenarios research aims to demonstrate, and assess issues related to, tokamak operation with
  - High non-inductive current drive fractions, enabling
  - Long pulses (wrt current relaxation, at least).
  - Control of current and kinetic profiles, leading to
  - Improved energy confinement

- The overall aim is to make a more attractive fusion reactor.

- Strong programs on many tokamaks. C-Mod focuses on issues where our tools, and/or plasma parameters, are unique and relevant to ITER and/or DEMO.
Some features of C-Mod relevant to Advanced Scenarios for burning plasmas

- **All-metal walls** (Mo, W).
- **All-RF heating and current drive** (ICRF, LHCD). No momentum or particle input. (Informs ITER. DEMO-relevant.)
- High field and density, leading to strongly coupled electrons and ions ($\tau_{e-i} << \tau_E$).
- High power density and heat flux (6-8 MW in 1 m$^3$ plasma, P/S\~ 1 MW/m$^2$, P/R\~ 10 MW/m, $q_{ll} > 0.5$ GW/m$^2$).
- Pulse length (2-5 s) long compared to current relaxation time $\tau_{CR} \sim 0.2$-1.4 s (due to compact size).
Significant progress on key control tools in past 2 campaigns.

Tools available or under development:

• Current profile:
  – Lower Hybrid Current Drive. 4.6 GHz, Phase I commissioned 2006; 1 launcher, 12x250 kW klystrons. Phase II planned FY09 – 2 new launchers, 16 klystrons.
  – Mode Conversion Current Drive.
  – Bootstrap current drive via pressure profile control.

• Density profile.
  – Cryopump controls edge source. (Commissioned 2007)
  – Control of core transport, peaking (via tailored ICRF, j(r)).

• Temperature Profiles
  – 8 MW ICRH, 40-80 MHz, 2 independently variable deposition locations.
  – LHRF heating.
  – Transport control (via tailored ICRF, j(r)).
Density Control

- **Issue:** Control of core and edge density is crucial for LHCD, our main off-axis current drive tool.
  - Recall $\eta \equiv \bar{n}_e l_p R / P_{LH}$
    
    $\eta \sim 1/N_{||}^2$, and increases with $T_e$.

- Accessible $N_{||}$ is also a strong function of local density, and $B$.
- Local $T_e$ also affects deposition.
- Control of $n_e$ as well as $T_e$ (via ICRF) is needed to get efficient, localized, off-axis CD.
- Control in both H and L-modes is needed.
Status: New cryopump performs well

- Cryopump was commissioned, and used routinely, in 2007 campaign.
  - Meets expected pumping speed, 9600 liters/sec (D\textsubscript{2}).

- Placed in upper vessel chamber; degree of pumping is controlled by magnetic balance.

- Novel design using radial slots, allowing good pumping for a wide range of shapes.

Details of design and performance in Poster NP8:83 by LaBombard et al, this session.
Excellent control of plasma density in L-Mode

- In L-mode plasmas, strong $n_e$ pumpout is observed. Density can be controlled at programmed levels, down to $\sim 7\times 10^{19}$ m$^{-3}$. Removal rate depends on magnetic configuration, $I_p$ and recycling regime.

- Can maintain $n_e$ even with strong gas injection (useful eg for impurity studies, or LHCD matching), or in presence of vessel or ICRF outgassing.
Density control in H-Mode is more challenging

- In typical LSN, higher $I_p$ H-modes, pedestal density still scales with $I_p$, largely set by transport. Cryopumping has weaker effect, mainly reduces $\nu^\star_{\text{ped}}$ by raising $T_{\text{ped}}$.

- Strong effect of topology (USN vs LSN vs near-DN) on both $n_{\text{ped}}$ and H-mode character is found, independent of cryopump!

- A clear demonstration of density control was obtained at lower $I_p$, and in USN, Rev $B_T$ plasmas. These steady 600 kA H-modes are promising targets for Advanced Scenarios.
  - Average $n_e 1.9 \times 10^{20} \text{m}^{-3}$
  - $n_{\text{ped}} 1.5 \times 10^{20} \text{m}^{-3}$.

Examples of 610 kA H-modes with cryopump, Rev. $B_T$, USN

See talk P03:04 by Jerry Hughes, this afternoon.
Plans: Explore and optimize H-mode density control using both cryopump and dynamic shape control.
Current Profile Control via LHCD
• **Issue:** Wave accessibility, CD efficiency and radial profile dependences in high density plasmas, B~5.4 T.
  – All prototypical of proposed system for ITER!
  – Want current drive **far off axis** \((r/a \sim 0.7-0.8)\) for broad \(j(r)\).

• **Status:** Phase I of LHCD system now operates routinely. Up to 1 MW coupled. Current drive results generally agree with expectations from modeling and empirical scalings.

For ohmic, L-mode target plasmas, \(N_\parallel=1.6\), typical LHCD efficiency is

\[
\eta \equiv \frac{n_{e,\parallel} R}{P_{LH}} \approx 3 \times 10^{19} \text{ m}^{-2}\text{A/W}
\]
Near-full CD achieved at $I_p = 1$ MA, with 0.8 MW LHCD

Ron Parker,
2006 APS invited
Radial profile varies with $N_{\parallel}$, as expected from modeling

- X-ray emissivity, an indicator of non-thermal electrons from LHCD, shifts further off-axis as $N_{\parallel}$ is increased – this gives some control over $j_{\text{LH}}(r)$.

- MSE also shows increase in j(r) off-axis.
  - Different discharge, with 680 kW LH, $I_p=0.82$ MA.

- Both measured x-ray and current profiles (from MSE) agree quite well with predictions of CQL3D model.
  - Note $j(\text{LH}) \sim 300$ kA is computed without $E_{\parallel}$, actual is higher.
**Issue:** LH Coupling into H-modes, and with ICRF

- 2006 experiments demonstrated good LH coupling into ohmic targets. Maintaining the right density at the grill mouth is key.

- It is known from other experiments that ICRF can interact with LHCD, via modifications to local density.

- LH coupling and current drive in H-modes is a key issue for ITER – and crucial for all advanced scenarios on C-Mod.
LH and ICRF have been successfully combined

- Good coupling is maintained when combining LHCD with ICRF from the E or J-port antennas.
- Increases in reflection do result with ICRF from the adjacent D-port antenna (due to decreasing local $n_e$).

**Plans:** New gas puff tubes have been added at the LH launcher. These will be used in the FY08 campaign, should improve coupling over a wider range of shapes, densities, and with ICRF.

Details in Poster NP8:69 by Greg Wallace et al, this session.
Fast electron profile broadens as $T_e$ is increased with ICRH.

- It is expected that, as $T_e(r)$ increases, LH waves will interact further off-axis, for given $N_{//}$ due to resonance.

- Unfavorable magnetic configuration was used to stay in ‘improved L-mode’, while heating with 2.4 MW ICRF.

- Broadening is observed in the non-thermal electron emission measured by hard x-ray camera, in qualitative agreement with modeling – detailed comparison with CQL3D is in progress.

- ICRF and LHCD have also been combined in current ramp, delaying sawtooth onset significantly. – See Poster NP8:67 by Kessel et al, this session
LHCD has been coupled into, *and even triggered*, H-modes.

- Reflection coefficients into ICRF H-modes are even lower than L-modes, though with higher fluctuations.
  - Boronization seems to make this easier.
- In some discharges with ohmic targets, the additional LH heating power triggered an H-mode.

- However, the launched power available (typically 400-600 kW in these experiments) was insufficient for significant current drive at H-mode densities.
  - Consistent with expectations, and with high-$n_e$ L-mode results.
Plan: Increase coupled LH power through optimized launcher, addition of second launcher.

- Current launcher has relatively large losses.
- Breakdown in air-side components limits power.
- A simplified design is in progress which should improve both issues.

- Two such launchers will be added in FY09.
- Will also increase source power to 4 MW (16 klystrons).

- Expect 2.5-3 MW coupled, meeting requirements for non-inductive scenarios identified by integrated modeling.

new launcher concept, featuring novel 4-way splitter.
• Modeling is key to planning both present experiments and longer-range, optimized scenarios.

• ‘Steady-state’ target is to produce fully non-inductive discharges with majority bootstrap current.

• A wide range of parameters \((n, B, q_{95})\) is being assessed with models, and will be explored experimentally, to address different issues and possible ITER scenarios.

• Many tradeoffs, for example:
  – Lower \(n_e\) increases LHCD, but can decrease bootstrap current.
  – Lower \(B\) increases \(\beta, \beta_N\), but reduces LH accessibility.
Several models in use or under development
(reviewed in invited talk by Paul Bonoli, JI1:003)

- **CQL3D** (R. Harvey): Self-consistent 2-D velocity space Fokker-Planck. (20-30% higher LHCD than ACCOME). Synthetic diagnostics of hard x-ray emissivity and ECE.
- **TRANSP**: Time dependent, predictive or simulation mode.
  - **LSC** for LHCD. Limitations in reverse $N_p$, 1 poloidal ray.
- **TORIC**: Full wave field solver for ICRH, mode conversion. Full wave treatment of LH recently achieved!
- **TSC**: Time dependent simulations with free-boundary equilibrium solver. Also LSC for LHCD. Being used to plan and model current experiments, scope and update scenarios.
  
  See poster NP8:67 by Kessel et al, this session.

Multiple codes, including TSC, TORIC and QCL3D, have recently been coupled as part of the Integrated Plasma Simulator. This should allow us to combine the strengths of each, and improve simulations!
Example: Low $n_e$, high LHCD scenario with TSC

- **Moderate, peaked density profile ($<n_e> \sim 10^{20} \text{ m}^{-3}$) is typical of C-Mod L-modes.**
- **Other parameters:**
  - 3 MW LH at $N_{//}=2.15$.
  - 3.5 MW ICRH
  - 5.4 T, 600 kA.
  - $T_{e0}$ 6.1 keV, $T_{i0}$ 4.1 keV
• **TSC modeling predicts 76% LH current, peaked at r/a ~0.8, and near-full non-inductive current drive.**
  - Note profiles are from a time-dependent simulation with self-consistent E, and are not completely relaxed.
• But, \( f_{bs} \) only 34%, due to low \( \beta_N \sim 0.95 \)
• Ideally wish to combine near-L-mode density with \( >H \)-mode energy confinement – recent ‘improved L-modes’ with USN or Reversed B are promising targets.
• Density profile ($n_{e,av} \sim 1.7 \times 10^{20} \text{ m}^{-3}$), is similar to H-modes obtained in 2007 campaign – not yet fully optimized.

• Other parameters:
  3 MW LH at $N_{//}=2.15$.
  3.5 MW ICRH
  5.4 T, 600 kA.
  $T_{e0} 5.6 \text{ keV}, T_{i0} 4.2 \text{ keV}$ (consistent with $H_{98}=1.2$, typical of C-Mod low $n$ H-modes)

Note: Low $\nu^*$ and higher $q_{95}$ H-modes typically exhibit $n_e$ peaking - Details in Talk PO3:5 by Martin Greenwald, this afternoon.
TSC model shows that LHCD remains far off-axis \((r/a \sim 0.7)\), reduced to 45% at the higher density.

- Higher \(\beta_N\) (1.2) increases bootstrap current, to 42%.

- Modest reduction in \(B\), and increase in confinement, would increase \(\beta_N\) and \(f_{BS}\), and should result in fully non-inductive discharge.
Hybrid scenario will be among first to be explored experimentally

• “Hybrid Scenario” is one of 3 main scenarios planned for ITER operation. Projections suggest it could extrapolate to Q=10 scenario with $q_{95}=4$, $q_{\min} \sim 1$, $\beta_N=2.8$, $H_H \sim 1.2$, $f_{NI} \sim 0.5$.

• While there is not yet a universally accepted definition, features include low central shear, with $q_0 \sim 1$, and improved confinement and stability over standard H-mode.

• On other experiments, flat $q$ is typically produced using heating and/or current drive in $I_p$ ramp, with strong NBI, and aided by NTMs.

• Several open issues for extrapolation to ITER can be addressed on C-Mod:
  – Can it be produced with coupled e-i, no particle or momentum input?
  – Can it be produced with $j(r)$ control by RF (without relying on MHD)?
  – If so, how do confinement, and MHD, compare?

• Modeling indicates $q_0 > 1$ is feasible with 1.2 MW LHCD, for 600 kA H-mode. In reach with Phase I LHCD; 1st experiments planned for 2008.
Summary

Significant recent progress has been made towards advanced scenarios on C-Mod:

• **Regimes of LHCD extended.** LH combined with ICRF, and coupled to H-modes. Control of location via variation of $N_{\parallel}$ or $T_e$ has been demonstrated.

• **Density control via cryopump and plasma configuration.** Best control achieved in L-mode. H-modes have dominant transport effects, further optimization is required.

• **Integrated and LH modeling improved.** Compares well with experiments.
Future Directions for C-Mod Advanced Scenarios

Modeling and experiments to date have highlighted areas for focus in improving scenarios, including:

- **Increased LH power** through upgrades.
- **Improved confinement** for increased bootstrap current – through $j(r)$ modification. ICRH and LHCD in rampup may be useful in reversing shear.
- **Improved H-mode density control**, optimizing both plasma configuration and confinement. Alternatively, explore regimes with higher $\tau_E$ but L-mode $n_e$.
- **Reducing $T_e$ peaking** through ICRF tailoring, to broaden ohmic and bootstrap current.
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