Integrated Scenarios: Alternate Regimes

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MIT PSFC

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Outline

• Introduction to C-Mod Alternate Scenarios program.
  – Scope
  – Motivation and goals.

• Main scenarios:
  – Hybrid/ improved H-mode.
  – Non-inductive.
  – I-mode.

  For each scenario, will present key recent results, issues and research plans to address them.

• Contributions to ITPA, ITER and broader fusion program.

• Summary
Alternate Scenarios: Scope and motivation

• A primary focus of the C-Mod (and world) research program is supporting the ITER H-mode baseline scenario. Covered by Steve Wolfe.

• Many other operating scenarios exist and are of potential importance for fusion, particularly as it moves to steady state operation – for ITER, for a Fusion Nuclear Science Facility and ultimately DEMO and a reactor. Each has its own advantages, and issues (generally less explored than ELMy H-mode).

• As a relatively small tokamak, with many fusion-relevant tools and parameters, we are well placed to explore potential scenarios, and to test key aspects of their physics.
  – Contributes to plasma control (particularly with RF tools), in scenarios which also feature DEMO-level fluxes to materials.
Primary scenarios under investigation

• “Hybrid” scenario (aka ‘Improved H-mode’ or ‘Advanced Inductive’).
  – H-mode confinement, with modified current profile which may give increased confinement or pressure. Offers prospect of increased non-inductive fraction, at lower current, of interest for ITER.

• Non-inductive scenario (aka ‘steady state’).
  – Current sustained by a combination of external (in our case LHCD) and bootstrap current – ideally dominant. Planned in second ITER phase, necessary for a FNSF.

• I-mode scenario
  – Features an H-mode like thermal barrier and energy confinement, with near L-mode particle confinement. C-Mod has pioneered study of transport, and demonstration of robust sustainment. Now poised to assess its benefits and issues as a potential BP scenario.
Hybrid Scenario

• 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.

• Can it be produced with LHCD on C-Mod? The anomalous density limit at $\sim 10^{20} \text{ m}^{-3}$ is a significant limitation, since H-mode is a high density regime.
  
  - 2010-11 experiments aim to assess the limit in H-mode. Since it is likely an SOL effect, is the same as in L-mode?

Bad news:

• Based on non-thermal measurements (HXR and ECE), LHCD, while non-zero, is likely low.

• “Density limit” still exists, though non-thermals are higher than in L-mode.
  
  – Can we improve with higher $B$, $N/\parallel$?

Good news:

• Successfully coupled LHCD into ICRF heated H-modes, with moderate current to reduce density ($\text{nebar} \sim 1.3-1.6 \times 10^{20}\text{m}^{-3}$).
Good News: H-mode is Improved by LHCD anyway!

- H-modes reproducibly had lower $n_e$, $P_{\text{rad}}$, much higher $T_e$, and often higher $W$, $H_{98}$ when LHCD applied in combination with ICRH – even assuming 90% LH is absorbed, which it likely is not.

H-mode ICRF

H- LH+IC

600 kA, 5.4 T, 3 MW ICRH, 0.8 MW LH
$\beta_p$ up to 1, $V_{\text{surf}}$ 0.2-0.3
Research plans for Hybrid/H-mode scenarios

- In FY11 and 12, will follow up on these intriguing but not understood results, likely related to pedestal.
  - Vary $N_{\parallel}$ (which was 2.3-2.5, just above $N_{\text{acc}}$) to lower and higher values (from no CD, to higher single pass absorption & CD).
  - Assess wider range of plasma parameters ($B_T$, $I_p$).
    - Is LHCD a robust means to control particle transport?
    - Optimize bootstrap fraction at higher $q_{95}$.
- Will also assess low $B$ (2.7-3.5 T), high $\beta_N$ regimes following promising recent H-mode experiments.
- Complete experiments using LHCD in $I_p$ ramp to modify $j(r)$, sawteeth BEFORE H-mode (the usual ‘hybrid’ recipe).
  - Begun but not completed in Feb. 2011.
  - Will then do analysis of CD and confinement to complete Research Goal.

Success in producing hybrid scenario via LHCD, with coupled e-i, no external momentum or core fueling, would be significant for ITER, and contribute to several ITPA experiments.
Non-inductive Scenarios

- Research seeks regimes which maximize the non-inductive current drive, ideally with high bootstrap fraction ($\beta_p$).
- As recommended by PAC, we have given top priority in 2010 to investigating the LHCD density limit and are revising target scenarios significantly in light of these results. Work in progress!

- As made clear in LH talk (and always expected), the additional launcher and LH power will be needed to realize goals. But, near-term research can assess physics in potential regimes. These include:
  - **Low density regimes**, with dominant LHCD, reversed shear, possible ITBs.
  - **Hot I-mode regimes**, moderate density, increased single pass absorption. Parameters similar in many respects to ITER SS scenario.
  - **H-mode regimes** (extension of hybrid scenario research.) Should give highest $f_{BS}$. Can we get high single-pass absorption and higher LHCD?
- A range of potential parameters ($N_\|$, B, $I_p$ etc) for each regime.
Approach from the low density fully non-inductive LHCD regime showed a promising initial result.

TRANSP analysis for 1101119007
5.4 T, 0.4 MA, n_e 6 x 10^{19} m^{-3}

LHCD driven current is off-axis and can produce a hollow current profile in ~100% non-inductive regime, leading to RS q profile. And, ITB development was observed in T_e.

Good consistency between experiments, including MSE-constrained EFIT, and TRANSP prediction.
Research plans for L-mode target scenarios

Planned experiments include:

• Heating with ICRF to increase $T_e$, increasing both single-pass absorption and bootstrap fraction.
  – Try Mode Conversion Heating, to avoid fast ion losses seen at low density and current. This has produced record C-Mod $T_e$ (8.5 keV) at 8T.
  – Note that non-inductive plasmas were sustained by only 900 kW LHCD power. We have a lot of headroom of heating.

• Raise $N_\parallel$ to increase LH deposition radius, single pass absorption; tradeoff with $\eta_{LH} \sim 1/N_\parallel^2$. Try compound spectra.

• Starting from hot, reversed shear plasmas, raise density. Can we keep good LHCD and modified shear, while increasing bootstrap fraction? What happens to ITB with coupled electrons and ions?

Non-inductive plasmas are also platforms for planned transport experiments, studying turbulence and ITBs, validating models.
LHCD in I-modes looks promising

- LHCD coupled to hot I-mode, (900 kA, 3.8 MW ICRH+0.6 MW LH, $T_{e0}$ 5 keV, $T_{ped}$ 0.8 keV).
- Non-thermal ECE and HXR were higher than in cold L-modes at same $n_e$ (1.3-1.4x10^{20} m^{-3}, above usual limit).

- Recent GENRAY-QCL3D modeling, including SOL, indicates limit is raised in hot plasmas, and could be further increased at higher $N_{//}$.

![Graph](image-url)
Research plans for I-mode target scenarios

Guided by experimental and modeling results, directions for improving I-mode target scenarios include:

- Reduce I-mode density range, perhaps at lower I_p which could also increase bootstrap fraction. (tradeoff w T_e)
- Raise N_\parallel to increase single pass absorption (tradeoff w \eta_{LH}).
- Try High B (8 T) I-mode for better accessibility, with favorable configuration to reduce P_{thresh}.

Notes: Core plasma parameters in high performance I-modes (~ 6 keV, 1.4e20 m^{-3}) approximate those in the original C-Mod AT scenarios, which were assumed to be H-mode and/or ITBs.
Integrated scenario modeling
(details in Bonoli talk)

- Integrated modeling is used to *plan* and *interpret* experiments.
- Currently we chiefly use TSC and TRANSP, both with LSC but run separately, for our time-dependent simulations.
- Using Fokker-Planck/ray tracing package CQL3D-GENRAY for more accurate analysis of LH deposition and current drive, for single time slices, synthetic diagnostics of x-rays, ECE for comparison to expts. Upgraded at MIT to include SOL. Use to assess, interpret \( n_e \) limit.
- Coupling GENRAY-CQL3D+SOL to integrated models is a high priority – progress made in 2010 but not yet complete. Pursuing 2 approaches:
  - Linking to **TRANSP**. GENRAY-LH inclusion nearly complete, slowed by PPPL personnel changes. Next coupling CQL3D, adding SOL.
  - Incorporate into **Integrated Plasma Simulator**.
    Will allow use with TSC, AORSA, other codes. Work underway as part of SWIM project (MIT, ORNL, PPPL, CompX). Expected in 2011.
- **Also advances in Full Wave LH codes at MIT**
  - TORIC-LH, linked to Fokker-Planck code CQL3D
  - LHEAF (FEM, also linked to F-P) developed to treat edge and core LH propagation, being adapted to handle numerical challenges of high \( n_e \) plasmas.
Example of integrated scenario extrapolating from I-mode plasmas

- Prediction from TSC, with experimental profiles, with $N_{\parallel}=3$, increased LH power.
  - In cases without a density limit, LSC gives LHCD in fair agreement with CQL3D.
  - 182 kA w 2 MW in this case.
  - Bootstrap fraction in this 900 kA I-mode plasma was low.

- Simulation at 650 kA, 8 T shows $f_{\text{BS}}$ 20%, 44% non-inductive and $q_0 > 1$ which may lead to $T_e$ increase.
- Once more models are coupled, aim to be able to predict effect of $j(r)$ on transport, profiles and vice-versa.
Other recent ‘trial scenarios’

- One of many in recent TSC parameter scans – lower $I_p$ (650 kA) gives higher bootstrap, higher $B$ (8 T) enables lower $N_{\parallel}$ (1.75), strong off-axis LHCD ~ 50% non-inductive.

- **Caveats:** Profiles (I-mode like $T_e$) not yet produced in expt at 8 T or 650 kA
  Action: FY12 experiments.

- LH profiles not yet checked for single pass absorption, potential SOL absorption.
  
  Action: CQL3D benchmark.

Further development (lower $I_p$ and/or broader $n_e$ and $T_e$ profiles) needed to optimize scenario. H-modes likely give higher bootstrap, challenge is to get strong LHCD.

If good high density LHCD is verified in strong single pass (L or I-mode), use to select LH
I-mode scenarios

- I-mode scenario features a strong thermal barrier but no particle barrier,
- A primary motivation for this research is for investigating barrier physics – *covered in Transport, Pedestal talks*.
- Pioneering work at C-Mod has shown that it is a robust new regime, which has attracted a lot of interest as potential operating regime for ITER and other devices.
- Seems timely to start investigating as an integrated scenario, with its own set of benefits, properties and issues. These include:

<table>
<thead>
<tr>
<th>Potential Advantages</th>
<th>Issues</th>
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<tr>
<td>ELM free</td>
<td>Robust access, L-I and I-H threshold</td>
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<td>Ease of density control</td>
<td>Density window, dependence? $P_{\text{fus}}$?</td>
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<td>H-mode like confinement, less power degradation?</td>
<td>Confinement scaling?</td>
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<td>No impurity accumulation.</td>
<td>Compatibility with seeding?</td>
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<td>Broader SOL footprint?</td>
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Major progress in expanding parameters and duration of I-mode

- Most C-Mod I-Modes on have been obtained with unfavorable $B \times \nabla B$ drift (mainly normal $B$ USN), which has increased L-H threshold.
  - Obtained for $B_\parallel$ 3-6 T, $I_p$ 0.7-1.3 MA.
- In 2010, obtained I-mode in LSN discharges with favorable drift, in the shape used for ELM studies ($\kappa \sim 1.5$, $\delta_L \sim 0.8$, $B_\parallel$ 5.4 T, $I_p$ 0.8-1 MA).
- 2011 experiments with Rev B, LSN (not shown) show wider power range for I-mode, dependence on divertor strike pt.
Energy confinement is in the range of H-mode scalings.

\[ \tau_{E,98,y2} \sim I_p^{0.93} n^{0.41} P_L^{-0.69} B^{0.15} \]

- Confinement near \( H_{98,y2} \) scaling in both configurations.
  - \( 0.8 < H_{98} < 1.25 \) at \( B > 5 \) T,
  - \( 0.6-0.9 \) at lower B.

- Absolute performance (W) is maximized where P threshold is highest – ie unfavorable drift, high B, high \( I_p \).
  - Do not see saturation with \( P_{\text{loss}} \).
- Can be maintained for duration of ICRF (10’s of \( \tau_E \)).

Eg. Discharge 1091016033
L-mode to I-mode
\[ \Delta W_{\text{MHD}} + 47\% \]
\[ \Delta <T_e> + 45\% \]
\[ \Delta <n_e> + 2\% \]
Research Plans for I-mode scenarios

- **Primary issue is robust access and sustainment**
  - Can we confidently enter and remain in I-mode, avoiding transitions to L or H-mode? Have many steady I-modes, but transitions do sometimes occur, at similar powers.
  - I-H threshold is a particular issue for burning plasmas, where power is not externally controlled.

- **Some planned experiments to address this include:**
  - Fueling into I-modes. Will I-H threshold increase?
  - LHCD into I-modes. Will particle transport be further increased as in H-mode pedestal, avoiding I-H transitions?
  - Exploration of shape dependences. Recent Rev B experiments indicating wider power window for I-mode are encouraging.
Other issues being addressed:

- **Density Range.** To date we have used a relatively small density window, largely due to operational issues (impurity generation, ICRF limits).
  - **Plans:** Reduce density, try wall conditioning (e.g. boronization). Will I-H threshold increase? Indications already of I-mode-like phenomena below H-mode low $n_e$ limit. Useful for advanced scenarios! Also try to increase density, with more ICRF for higher absolute performance.

- **Optimize and characterize confinement and performance.**
  - While I-mode confinement is in the H-mode range, there is no reason to expect exactly the same scaling. Have indications of less power degradation of $\tau_E$ — so closely coupled to I-H threshold issue.
  - **Plans:** Assess affect of wall conditioning. Further expand range of shapes and plasma parameters — including favorable drift. Lead ITPA intermachine experiments. Develop confinement scaling, for ITER prediction.

- **SOL heat footprint, need for and compatibility with radiative divertor?**
  - **Plans:** Measure heat flux (analysis in progress), try seeding more systematically (already used to reduce injections at high RF power).
Core-edge integration

With a strong Boundary program, and record SOL heat fluxes (upstream $q_\|/\varepsilon$ exceeding ITER, approaching DEMO), C-Mod is very well placed to address the issues of integrating advanced scenarios with tolerable edge fluxes. Supports increasing FES emphasis on material issues, FNSF.

Edge integration is in fact a requirement, since all scenarios require use of high ICRF and/or LHCD power, and need clean plasmas. In both cases high Z impurity injections can be an issue – for LHCD particularly at high density, further evidence of power deposition in the edge.

- Resolving RF-wall effects is critical. Our experience is very relevant to ITER, could influence W vs C PFC decision. New 4-strap antenna will be tested in 2011. Do influxes decrease? Do LHCD influxes decrease in high single pass scenarios?

- For all scenarios explored, we will optimize, document pedestal and SOL/divertor parameters. (ITPA PEP-20)

- Will attempt integrating with radiative divertor following good success in high power H-mode scenarios. Already use Ne seeding in many I-modes.

- Divertor heat fluxes will be a particular challenge for alternate scenarios due to lower density and longer pulses.
  - Local T rises may limit pulse duration at full power to 3-4 s (still several $\tau_{CR}$). Will test materials (W tiles), techniques such as sweeping, to their limits. Motivates DEMO-like divertor upgrade.
Key Contributions to ITER

• The C-Mod integrated scenarios research programs are both primarily aimed at contributing to ITER scenarios – we feel our parameters and tools are extremely relevant.

• This is reflected in many anticipated contributions to ITPA/ITER high priority research needs. Active in several ITPA joint experiments.

Some of the most important and unique contributions expected are:

• Establishing Basis for H&CD Upgrade program.
  – Test LHCD as for non-inductive CD (volt-s reduction) and j(r) control tool, for \( I_p \) ramp and for both hybrid and steady state scenarios, at the ITER field and density. **New IOS 5.3.** Is \( n_e \) limit raised with single pass absorption, which is expected on ITER?

• Development of hybrid/steady-state plasma scenarios and experimental validation. Key tests of access and performance with coupled electrons and ions, actual pedestals, without fuelling or momentum input

• Assessing I-mode as a potential ELM-free, high confinement scenario for ITER. ITER has urgently requested increased research in alternate approaches to RMP and Pellet pacing of Type I ELMs.
Expected contributions to ITPA Experiments

Active experiments, will continue:

• IOS-5.3: Assessment of lower hybrid current drive at high density for extrapolation to ITER advanced scenarios.
• IOS-4.1: Access conditions for hybrid with ITER-relevant restrictions
• PEP-22: Controllability of pedestal and ELM characteristics by edge ECH/ECCD/LHCD
• I-mode transport and pedestal studies (TC-18, TC-19*, PEP-31*)

Planned for FY2012:

• IOS-5.2: Maintaining ICRH Coupling in expected ITER regime
• IOS-6.1: Modulation of actuators to qualify real-time profile control methods for hybrid and steady state scenarios.

If hybrid scenario successfully accessed:

• PEP-20: Documentation of the edge pedestal in advanced scenarios
• IOS-4.2: $\rho^*$ dependence on transport and stability in hybrid scenarios
• TC-5: Determine transport dependence on Ti/Te ratio in hybrid plasmas

Deferred to Phase II LHCD 2013 (need higher LH power):

• IOS-3.1: Define access conditions to get to SS scenario
• TC-5: Determine transport dependence on Ti/Te ratio in steady-state scenario.
C-Mod Alternate Scenarios research contributes to ReNeW Thrusts

Particularly to Theme II “Creating predictable, high performance, steady state plasmas” but also to Theme I “Burning plasmas in ITER”, Theme III: Taming the Plasma-Material Interface”. These in turn directly address Issues & Gaps in 2007 FESAC report.

Contributions to proposed actions in specific Thrusts include:

• Thrust 4: Qualify operational scenarios and supporting physics basis for ITER – See “contributions to ITER/ITPA” on prior slides.

• Thrust 5: Expand limits for controlling and sustaining fusion plasmas
  – Develop and test T, j, density control methods (notably IRCH, LHCD, transport, rotation control) at DEMO-relevant $n_e, B$, for multiple $\tau_{CR}$.

• Thrust 6: Develop predictive models & challenge with experiments
  – Improvements of RF and integrated models, and testing against integrated scenarios under unique conditions.
Further contributions to proposed actions in specific Thrusts include:

- **Thrust 8: Dominantly self-heated and self-sustained burning plasmas.**
  - Assess potential extensions to ITER advanced scenarios. C-Mod work will inform LH upgrade decision and through model benchmarks, give more realistic scenario assessments.
  - Also informs designs for any alternate SS BP experiment, which would likely be compact, high B and RF-driven.

- **Thrust 12: Demonstrate integrated solution for plasma-material interfaces compatible with optimized core.**
  - Key challenges are integrating high power density, elevated wall temperature, and long-pulse sustainment. C-Mod results, particularly with hot wall divertor upgrade, should provide the design basis for tokamak approach to a dedicated PMI facility a la VULCAN.

- **Thrust 13: Science and technology for fusion power extraction of and tritium sustainability.**
  - Provide key data for design of tokamak approach to a Fusion Nuclear Science Facility a la FDF (eg, LHCD in high n_e H-modes)
Alternate Integrated Scenarios: Summary of results, priorities and capabilities

2010: LH2 launcher; ~1 MW LH, 0.5 s – successfully commissioned.
✓ Begin assessment of LHCD efficiency and limitations at high density, in a range of regimes, combination with ICRF. (joint with LH physics group)
✓ Development of robust I-mode scenarios in favorable and unfavorable configurations.
✓ Demonstrated non-inductive, reverse shear plasmas with LHCD, at low n_e.

2011-12: New klystrons; protection, cooling upgrade for longer LH pulses
~ Complete experimental assessment of high density LHCD, extend to single pass abs.
~ Hybrid scenario (C-Mod Milestone)
~ LHCD into Improved L-mode targets.
~ Understand and exploit LH effect on H-mode pedestals (joint w Pedestal, LH groups)
• Optimize I-mode performance, expand op space, lead multimachine experiments.
• Begin longer pulse experiments and integration with impurity seeding.
• Increase heating power and density in non-inductive scenarios.
• Upgrade and validate LH models of high density edge effects (C-Mod FY12Milestone).
• Continue development and integrated modeling of alternate scenarios, depending on 2011 results. (C-Mod FY12 Milestone on low ν* I-mode.) Plan for…

2013+: LH3 Launcher, divertor upgrade, second 4-strap ICRH, all critical to higher performance, longer pulse alternate scenarios!