C-Mod Research for Integrated Scenarios on ITER:
Advanced Scenarios

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*With contributions from all thrust participants!*

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Outline

• Review of long term and near-term goals and topics emphasis.

• Overview of progress in 2006.

• Plans for 2007 (most of talk).

• Relations to other programs, and brief look beyond 2007.
Key topics and goals of advanced scenarios program (from 5-yr plan)

1. **Current profile control, and non-inductive current drive, using LH and ICRF waves, at high densities ($>10^{20}$ m$^{-3}$) for pulse lengths long compared to current relaxation times.**
   $\omega_p, \omega_c$ are key parameters for wave physics – C-Mod is very similar to ITER. Long pulse will enable fully relaxed non-inductive current profiles (note C-Mod has $\tau_{CR}=0.1-1$ s, has run 3 s pulses, TF limit 5 s).

2. **Understanding, control and sustainment of Internal Transport Barriers, in LH and ICRF driven regimes with strongly coupled ions and electrons, $\tau^{e-i} << \tau_E (T_e \sim T_i)$.**
   Will ITBs form in ITER, with strong electron-ion equilibration and low particle or momentum source? Electron, ion, particle transport channels often respond differently in barriers.

3. **Optimize no-wall $\beta$ limits ($\beta_N \sim 3$).**
   ITER ‘steady-state’ operation is currently planned to be in this range.

Note: Because of the similarity in parameters and challenges, C-Mod considers this thrust a key part of our ITER support.
Potential advanced steady-state target scenarios on C-Mod modeled with ACCOME

- One of many optimized scenarios modeled with ACCOME.
  - $I_{LH} = 240$ kA (28%)
  - $I_{BS} = 600$ kA (70%)

$P. ~Bonoli, ~Nucl. ~Fus. ~20(6) ~2000$

- $B_T = 4$ T
- ICRH: 5 MW
- LHCD: 3 MW, $N_{//0}=3$ (Phase II)
- $n_e(0) = 1.8 \times 10^{20} ~m^{-3}$
- $T_e(0) = 6.5$ keV
- $\beta_N = 2.9$ – at no-wall limit.
- Edge and core transport barriers.

Notes: $\beta_N = 2.9$ requires $H=2.5$, assumed to result from reversed shear (LHCD)
$n_e$ is lower than current H-modes (cryopump)
Near-term focus on developing, using profile control tools

“The crucial distinguishing feature of an Advanced Tokamak over a conventional tokamak is ...the use of active control of the current or shear profile, and of the pressure profile or transport characteristics”

(AT Workshop, GA, 1999)

- **Current profile:** Lower Hybrid Current Drive. 4.6 GHz
  (Phase I operating; 3 MW source, 1-1.5 MW coupled. Phase II 2009; 4 MW source, 2.5-3 MW coupled, 2 launchers with independent phasing, N//.  
  - Bootstrap current drive via pressure profile control.

- **Density profile.**
  - Control of core transport, peaking.
  - Cryopump controls edge source. (New in 2007)

- **Temperature Profiles**
  - 8 MW ICRH, 40-80 MHz, 2 independently variable deposition locations.
  - LHCD.
  - Control of core transport via RF deposition, magnetic shear.

2006 PAC recommended, and we fully agree, that we “continue aggressive development of these tools” (ie LHCD, cryopump, j(r) measurements). Big efforts on all 3 in 2006, expect payoff in 2007.
Major Milestone in 2006 was LHCD

- As shown in LH talk by Ron Parker, C-Mod exceeded target for 2006 campaign (which was 500 kW). Coupled > 900 kW.

- Also exceeded CD target; > 80% non-inductive (transient $V_{\text{loop}}=0$) at 1 MA. (‘Phase I’ target was 50% non-inductive).

- Implemented non-thermal diagnostics, extensive modeling of LHCD experiments, with generally good agreement; Further work is in progress.
BUT: There’s a long way to go

- For the first (2006) full campaign, we decided not to try to use LHCD in integrated scenarios, but devote time to developing, testing system.
- All experiments were L-mode, with ohmic targets, most quite low $\bar{n}_e$ (3-6 x $10^{19}$ m$^{-3}$).
- Maximum power of 1 MW is well below what we would need for fully non-inductive high-bootstrap regimes.

- In FY07 campaign, in parallel with further LH-specific experiments outlined by Ron, we intend to start using LHCD in integrated scenarios with higher heating power and confinement.  
  Key LH challenges, all also critical for ITER (and GA’s FDF):
  - Combining LH and ICRF
  - Coupling LH into H-mode
  - Good LHCD at higher $n_e$.

Top priority of advanced integrated scenarios thrust for 2007!
Transport and bootstrap current control

- We continue to consider transport control important for tailoring pressure, and therefore bootstrap current, profiles. Good progress in understanding physics mechanisms (covered in Transport).

- In 2006, started experiments on lower $I_p$ ITBs. Aims are:
  - Increase $f_{BS}$.
  - Demonstrate active control of $j(r)$ by dynamically varying on-off axis mix, and ITB formation.

C. Kessel, Ideas07
Low $I_p$ ITBs demonstrated

- First phase of this experiment was to make ITBs at progressively reduced $I_p$
- Found barriers still readily produced at 4.5 T, 450 kA, with 80 MHz off-axis ICRF.
  - Technical difficulties on the day with the central heating at 70 MHz, leading to impurity accumulation and making conditions transient.
- Even in H-mode phase, TSC calculations show ~ 22% bootstrap fraction
  - Expect > 30% with good ITB, some core heating.
- Will continue these experiments in 2007, and later combine with LHCD – note $n_e$ is compatible.
  - $j(r)$ diagnostics important.
High Priority Experiments for 2007

~20 new and prior ideas in this thrust considered following Ideas forum. Of these, the top priority for next campaign include:

• Producing "hybrid scenario" on C-Mod with LHCD.
• Documenting pedestals in advanced scenario regimes.
• Lower $I_p$ Long Pulse L- and H-mode Scenarios.
• Studying LHCD (j-control) effect on ITBs.
• Development of a reversed shear scenario.
• Modification of j(r) through H to ITB cycle (continuation of 2006 expt).
• Extending 2-Freq ITBs to higher power and performance (con’t).

In almost all cases, success of integrated scenarios depends on tools or target plasmas to be demonstrated in other topical groups. Eg.

• LHCD in RF heated H-mode.
• Low n H-modes and ITBs, aided by cryopump.
• j(r) measurement via MSE.

Modeling of these scenarios is also ongoing. Many will need >1 run day. Therefore, we will maintain flexibility in prioritization and run planning! Will present details of a few of these planned experiments for illustration.
Hybrid scenario using LHCD

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

• While there is not yet a universally accepted definition, features include:
  – Improved confinement and stability over standard H-mode.
  – Low central shear, with $q_0$ near 1. (small or no sawteeth).
  – Often high $\beta_N > 2$.

• Several open questions for extrapolation to ITER (from ITPA research topics).
  – Can it be produced with coupled e-i, no particle or momentum input?
  – Can it be produced with external LHCD, rather than relying on (poorly understood) MHD effects?

• C-Mod is well placed to answer these!

• Would contribute to several ITPA SSO/TP experiments, databases, including documenting pedestal in advanced regimes.

Co-proposed by Sips, IPP Garching
TSC shows LHCD into demonstrated H-mode Plasmas Can Produce High $f_{NI}$ and Drive $q(0) > 1$

C. Kessel

TSC modelling used $n_e(r)$, $T_e(r)$ from an actual C-Mod ‘low n’ H-mode (600 kA, 5.4 T).

- Indicates $q_0$ should be $> 1$ with available LH, but $q(r)$ may not flatten enough; should separate effects on confinement.

Directions for improvement include
- **Cryopump** to reduce $n$, raise $T_{ped}$ and $j_{LH}$.
- Broadening $T_e(r)$ using **off-axis ICRF**.
Lower $I_p$ scenarios should lead to higher non-inductive fractions, enable future long pulse

- **Other planned scenarios use reduced $I_p$ (400-450 kA) to maximize non-inductive current fraction with available $P_{LH}$.
  - 2006 expts achieved $f_{BS} \approx 22\%$ in H-mode, without LHCD. Prior TRANSP modeling shows adding LHCD should amplify this.
- Explore adding LHCD in $I_p$ ramp to see effect on $j(r)$.
  - Likely different than other experiments due to short $\tau_{CR}$ on C-Mod.
- Both L-mode and H-mode regimes are of interest; also ITBs for greater $f_{BS}$ (will not be time for all options in 2007).
Transport control/barrier experiments will focus on effects of shear

- To date, we have been studying ITBs with ‘normal’ shear – in contrast to most other experiments.
- Now that current profile control tool is available, we will focus on studying effects of magnetic shear on transport, ITB formation and properties.
  - First step in 2007 will be to add LHCD to ITBs formed using off-axis ICRF.
  - How does shear change affect ITB threshold, and foot location?
- In future phase, will study ITBs produced by LH shear reversal.
- All experiments will be in ITER-relevant regime with coupled electrons and ions, no momentum or particle input, pulse length > $\tau_{CR}$.

All of particular importance for ITBs.

2007 experiments will use as LH target the low $n_e$ ITBs being developed in the Transport topical area.

4.5 T, 700 kA, ITB in ELMy H-mode
Relation of C-Mod Integrated Scenarios research to other programs

• C-Mod H-mode and advanced scenarios research is well aligned with US science program priorities, esp.
  – Carry out additional science and technology activities supporting ITER.
  – Predict the formation, structure, and transient evolution of edge transport barriers.
  – Integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas.
  – Extend understanding and capability to control and manipulate plasmas with external waves.
  – Resolve the key plasma-material interactions, which govern material selection and tritium retention for high-power fusion experiments.

• Will emphasize ITPA high-priority tasks and inter-machine experiments. For advanced scenarios, primary relation is to Steady State Operations and Transport Physics groups.

• Expect increasing involvement with, and response to, BPO topical groups (esp Integrated Scenarios), and ITER WG tasks.
  – This is tricky at present since we don’t yet know which will be designated high priority. However, C-Mod work is aligned with a number of issue cards submitted by BPO and ITPA, and program remains flexible. We expect to inform ITER decisions re LHCD.
Future needs and plans for Advanced Integrated Scenarios Thrust

• Looking beyond 2007, we will progressively move towards higher bootstrap fraction and confinement scenarios, with goal of steady-state, 100% non-inductive current drive, 70% bootstrap, up to no-wall limit ($\beta_N \sim 3$).
  – C-Mod target is very similar to ITER steady-state scenario 4.

• However, recent modeling has reconfirmed that we need to significantly increase coupled LHCD power (to at least 3 MW).
  – $j(r)$ in higher $n$ H-modes will be challenging.
  – Fully expect that 2007 experimental results will make the need for more power even clearer!

• For these reasons, **we will move aggressively to increase $P_{LH}$**
  – Commission 12 klystrons to max 3 MW (done this shutdown).
  – Replace first coupler (operation in FY08) – full 96 guides.
  – Install second launcher (operation in FY09).
  – Reduce system losses (launcher redesign, other modifications).
  – Add more klystrons (4 in FY09, 4 more budget-dependent.)
Summary: C-Mod Research for Advanced Integrated Scenarios on ITER

- 2006 was a very productive year in developing control tools and plasma targets for advanced scenarios.
  - LHCD demonstrated, up to 900 kW coupled, good efficiency.
  - Cryopump fabricated.
  - Lower $I_\text{p}$ and lower $n_\text{e}$ Internal Transport Barriers developed.

- In 2007, the thrust will begin using and integrating these tools to develop new plasma scenarios. Priority given to those which exploit the new tools (especially LHCD), and seem within reach with the power available (up to 1.5 MW coupled).
  - Hybrid scenario.
  - Lower $I_\text{p}$ H-modes with larger non-inductive fraction.
  - Effect of shear on ITBs.

We are excited to be able to begin these experiments, after years of preparation!

- Results will be critical in informing our five-year plan, which will extend research to fully non-inductive scenarios, as well as addressing key issues for ITER advanced scenarios.