FY11 FES Joint Research
Target: C-Mod Highlights

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J. Myra, D. Russell, Lodestar

Alcator C-Mod FY11 Q4 Quarterly Review
27 October 2011
Predictive capability for the H-mode pedestal was the subject of the FY11 JRT

Statement of the FY2011 FES Joint Theory and Experiment Research Target

Improve the understanding of the physics mechanisms responsible for the structure of the pedestal and compare with the predictive models described in the companion theory milestone. Perform experiments to test theoretical physics models in the pedestal region on multiple devices over a broad range of plasma parameters (e.g., collisionality, beta, and aspect ratio). Detailed measurements of the height and width of the pedestal will be performed augmented by measurements of the radial electric field. The evolution of these parameters during the discharge will be studied. Initial measurements of the turbulence in the pedestal region will also be performed to improve understanding of the relationship between edge turbulent transport and pedestal structure.

A focused analytic theory and computational effort, including large-scale simulations, will be used to identify and quantify relevant physics mechanisms controlling the structure of the pedestal. The performance of future burning plasmas is strongly correlated with the pressure at the top of the edge transport barrier (or pedestal height). Predicting the pedestal height has proved challenging due to a wide and overlapping range of relevant spatiotemporal scales, geometrical complexity, and a variety of potentially important physics mechanisms. Predictive models will be developed and key features of each model will be tested against observations, to clarify the relative importance of various physics mechanisms, and to make progress in developing a validated physics model for the pedestal height.
Predictive capability for the H-mode pedestal was the subject of the FY11 JRT

- **Simplified Goal:**
  - Improve our knowledge of the physics processes that control the H-mode pedestal by applying models of these mechanisms to experimental data.

- Alcator C-Mod, DIII-D and NSTX devoted significant experimental resources to pedestal studies

- C-Mod experimental work in ELMy and EDA H-mode, I-mode

- Collaborations among facilities, and with theory/modeling groups increased

- Some physics mechanisms evaluated
  - Peeling-balloon (PB) stability
  - Kinetic ballooning modes (KBM)
  - Resistive ballooning modes
  - Electron temperature gradient (ETG) modes
  - Neutral fuelling
  - Neoclassical transport, flows, bootstrap current
  - Paleoclassical transport
# Quarterly targets and corresponding contributions from C-Mod

<table>
<thead>
<tr>
<th>Joint Quarterly Targets</th>
<th>C-Mod Activity</th>
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<tr>
<td><strong>Q1</strong></td>
<td><strong>Experimental campaign</strong></td>
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<td>Develop a preliminary research plan coordinated among the three facilities, delineating the planned experiments. Provide to the theoretical community a sample set of existing preliminary pedestal data suitable for initial comparisons with simulation. Develop a preliminary coordinated research plan for simulation activities, delineating a planned set of simulations aimed at comparison with experiment.</td>
<td>Completed first round of EPED validation experiments (current, shape scans) Perform additional pedestal experiments (species dependence, pedestal control, separation of particle and energy barriers)</td>
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<td><strong>Q2</strong></td>
<td>Completed 2nd round of EPED validation experiments (field scan) Obtained enhanced data sets in EDA H-mode Pursued I-mode characterization experiments</td>
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<td>Initial planned experiments will have been carried out on at least one of the three facilities and results conveyed to the theoretical community. Initial comparison of theory and experiment using the existing sample data set will have been carried out with at least two models. Results from the comparison will be conveyed to the experimental community to inform plans for remaining experiments.</td>
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<td><strong>Q3</strong></td>
<td>No C-Mod operation; up-to-air for installation of new 4-strap ICRF antenna (DIII-D did operate, and a joint experiment was run there to obtain a dimensionless match to C-Mod ELMy H-mode)</td>
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<td>Continue experiments with results made available to the theoretical community. Comparison of theory and experiment will be extended to include a broader set of experimental conditions. Based on the results of experiments and simulations, remaining experimental plans will be adjusted and simulation models will be refined and extended.</td>
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<tr>
<td><strong>Q4</strong></td>
<td>Complete experiments and simulations. Compare key features of relevant theoretical models against observations to clarify the relative importance of various physics mechanisms. Submit a report documenting completion of these activities.</td>
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Pedestal research received extensive experimental time in recent campaigns.

<table>
<thead>
<tr>
<th>MP</th>
<th>Topic</th>
<th>Approx. Run time (days)</th>
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<tr>
<td>564, 630</td>
<td>Power and radiation requirements for $H_{98}&gt;1$ H-modes with impurity seeding</td>
<td>FY10: 3</td>
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<tr>
<td>578</td>
<td>Experimental tests of EPED1 pedestal prediction in ELMy H-Mode</td>
<td>FY10: 3</td>
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<td>579</td>
<td>Characterization and optimization of I-mode</td>
<td>FY10: 6</td>
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<td>580</td>
<td>Comparison of Type I ELM access and characteristics in He4 and D plasmas in C-Mod</td>
<td>FY10: 1</td>
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<td>595</td>
<td>Analysis of the Radial Impurity Transport at the Pedestal Region</td>
<td>FY10: 1</td>
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<td>614</td>
<td>Pedestal modifications with lower hybrid in EDA H-mode</td>
<td>FY10: 1</td>
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<td>636</td>
<td>Study of ELMy H-mode: Toroidal field scan</td>
<td>FY10: 1</td>
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<td>644</td>
<td>Edge profiles and fluctuations in EDA and ELM-free H-Modes</td>
<td>FY10: 1</td>
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<td>654</td>
<td>I-mode with lower single null and unfavorable grad-B topology</td>
<td>FY10: 1</td>
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<tr>
<td>655</td>
<td>Characterization of WCM behavior and estimates of transport at the edge</td>
<td>FY10: 1</td>
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<tr>
<td></td>
<td><strong>Totals:</strong></td>
<td>FY10: 10</td>
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</table>
Recent experiments have expanded ELMy H-mode operating space on Alcator C-Mod

- Type I ELMing pedestal thought to be manifestation of ultimate pressure limits in baseline H-mode
- New experiments to examine pedestal scaling over expanded operating space
- Linear stability analyzed with ELITE, comparisons with EPED predictions made
- Makes contact with H-mode on other devices (e.g. identity experiment with DIII-D)
Recent experiments have expanded ELMy H-mode operating space on Alcator C-Mod

\[ \delta_{\text{lower}} > 0.75 \]
\[ \delta_{\text{upper}} \sim 0.15 \]
Recent experiments have expanded ELMy H-mode operating space on Alcator C-Mod

More extreme shaping, density reduction crucial to access to larger, regular ELMs
Recent experiments have expanded ELMy H-mode operating space on Alcator C-Mod

- Prior studies mostly restricted to 5.4T, 0.9MA, elongation less than 1.5
- New data: $0.45 < I_p [\text{MA}] < 1.05; 3.5 < B_T [\text{T}] < 8.0; 1.42 < \kappa < 1.56$
- Evidence of pedestal width scaling inversely with $I_p$
- Upper range of $\beta_p$ extended
- Width data consistent with $\beta_p^{1/2}$ scaling, with little or no trend on other parameters → consistent with scaling from kinetic ballooning argument

J.R. Walk, paper in preparation
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\[ J.R. \text{ Walk, paper in preparation} \]
ELITE calculations show proximity to p-b stability boundary

Note: Equilibria are preliminary. Pressure gradients in reconstruction underestimate likely experimental gradient.
How do profiles and stability compare in recent C-Mod/DIII-D matching exp.?

- Attempted to match non-dimensional parameters at pedestal top: $\beta$, $v^*$, $\rho$
- Preliminary stability diagrams and loci of experiment are similar
- Similarities observed in experimental ELM signatures, inter-ELM fluctuations
  - Note: Imperfect match in pedestal density profiles; stands in contrast to prior EDA H-mode identity studies [D.A. Mossessian, Phys. Plasmas 10 (2003) 689]
How do pedestals compare with latest EPED predictions?

- EPED 1.63 is the latest iteration of Snyder model incorporating
  - KBM constraint on the width, evaluated using ideal ballooning stability over a determined range of pedestal
  - Peeling-ballooning stability evaluated using linear growth rates corrected for diamagnetic stabilization

- Ratio of predicted $p_{ped}$ to experimental is ~1.1—1.2
  - Experimental data are ELM-averaged, not ELM-binned here, and so in principle underestimate pressure before the ELM
  - Prediction is also very sensitive to the diamagnetic model chosen --- a point for further investigation

- Width prediction matches to within the error bars of experiment

J.R. Walk, paper in preparation
C-Mod data have extended EPED validation to high absolute pressures

Comparison of EPED Model to 273 Cases on 5 Tokamaks

- JET (137)
- DIII-D (91)
- C-Mod (24)
- JT-60U (16)
- AUG (5)

P.B. Snyder, 2011 H-mode Workshop
EDA H-mode stability examined using data set generated for the FY11 JRT

- Representative EDA discharge with no ELMs
  - Pedestal regulated by QCM fluctuation in density, magnetic field
  - $f_{\text{QCM}}$ of main harmonic between 50 and 100kHz (typical)
  - Toroidal mode numbers $n \sim 13$—16
- Profiles and equilibrium reconstructed at 0.9s
EDA H-mode stability examined using data set generated for the FY11 JRT

- Pedestal structure, stability, turbulence being studied with multiple simulation codes:
  - BOUT++ (LLNL)
  - M3D (MIT)
  - ELITE (GA)
  - SOLT, 2DX (Lodestar)
  - XGC0 (PPPL)

X.Xu, 2011 H-mode Workshop
EDA H-mode stability examined with BOUT++

- EDA H-modes are relatively resistive: $S \approx 10^6$ rather than $\sim 10^8$ or $10^9$
- Stable to ideal MHD (ELITE agrees)
- Increased resistivity increases computed linear growth rates

[Graph showing Lundquist Number Profile with $S=10^6$]

- Trends of linear growth rates with $\eta$, $n$ found to be in agreement with resistive ballooning theory

[Graph showing $n=15$ Growth Rates vs. Time]

X. Xu, 2011 H-mode Workshop
Diamagnetism stabilized higher n modes

- Diamagnetic term has been seen to stabilize peeling-ballooning modes at high n, but with a smoother roll-off
- Growth rates peak sharply for n<30; QCM mode numbers tend to be in the 10—25 range
- Modes found to propagate in the e− direction, as observed in experiment
- Results of first non-linear run are being examined, and will be discussed at APS
Additional modeling of the EDA pedestal is taking place

- **M3D simulations (L. Sugiyama)**
  - MHD code capable of examining edge stability with varied resistivity, flows
  - Simulations with initial input data sets have found relative stability for n≤23, except at artificially high values of resistivity
  - Work proceeding on case with high resolution kinetic equilibrium reconstruction, with flows
  - Treatment of the high edge current and density at the separatrix being looked at

- **Lodestar modeling EDA edge with two codes: SOLT, 2DX**
  - SOLT: non-linear fluid code that models turbulence (including arbitrary δn/n amplitude blobs)
  - FY10 JRT work with SOLT showed a quasi-coherent oscillation with some qualitative similarities to the QCM, some differences
    - QC feature in SOLT results from density fluctuations originating in strong gradient region
    - Responsible for cross-field transport fluxes, which helps set the SOL width in simulation
  - 2DX: toroidal geometry, linear eigenvalue code
    - Tests wide variety of physics models with realistic divertor geometry, edge/SOL profiles
    - No single candidate has yet emerged to explain the QCM
  - SOLT/2DX results taken together imply that nonlinear physics, perhaps mode coupling, fundamental to explaining QCM

*J. Myra, D. Russell will report on progress at APS*
Profiles and fluctuations in \( l \)-mode studied experimentally

- Highlights of experimental \( l \)-mode research previously discussed at Q3 review by A. Hubbard
  - Temperature pedestal without a density pedestal
  - Decoupling of particle and thermal transport maintains good confinement steady state, while staying below ELM stability limits
- Many new experimental results, suitable for modeling
  - \( T_{\text{ped}} \) formation associated with \textit{selective} turbulence suppression
    - Mid-range (60—150kHz) fluctuations suppressed
    - Persistent turbulence at 200-300kHz \( \rightarrow \) weakly coherent mode (WCM)
    - WCM vanishes upon formation of H-mode density pedestal
  - Mid-range turbulence decrease well correlated with \( \chi_{\text{eff}} \) drop *
  - WCM: Fluctuations in \( T_e \) accompany \( n_e \), \( B \) fluctuations (\( \delta T_e/T_e \sim 1\%) \dagger
  - WCM: Typ. \( n \sim 10-25 \), \( k_{\perp \rho_s} \sim 0.1 \), electron diamagnetic propagation, lab frame freq. increases with \( T_{\text{ped}} \)
  - Fast magnetics indicate amplitude of WCM peaked off-midplane, in \( e^- \) diamagnetic direction

* Hubbard, Phys. Plasmas \textbf{18} 056115 (2011)
† White, Nucl. Fusion, to be published
Summary and Plans (I)

• **ELMy H-mode**
  
  - Pedestal scalings are in broad agreement with expectations from width limited by KBMs, height limited by PBMs
    
    • $\Delta \sim \beta_p^{1/2}$, $p_{ped} \sim I_P$, gradient effectively limited by $\alpha_{crit}$
    
    • Comparisons to EPED model show agreement to within 20%; efforts are in progress to improve the accuracy of experimental reconstructions and improve validation of the model
  
  - Linear $p$-$b$ calculations with ELITE using reconstructed profiles/equilibrium in the last 20% of ELM cycle show proximity to stability boundary; comparisons to matched discharges on DIII-D corroborate this
  
  - Experiments are proposed to seek signatures of KBM in fluctuations --- magnetics probe will be available in FY12 campaign
Summary and Plans (II)

• EDA H-mode
  – Calculations with ELITE and BOUT++ show the EDA pedestal is ideal MHD stable
  – BOUT++ study of resistive, diamagnetic effects yield instabilities at \( n<30 \), with modes propagating in the \( e^- \) diamagnetic drift direction --- promising consistency with experiment
  – Non-linear simulations with BOUT++ using full flow measurements as input will implemented; \textit{this should predict turbulence driven transport}
  – Complimentary studies ongoing with M3D, SOLT, 2DX
  – Ongoing research aimed at understanding what limits pedestal growth, rather than peeling-balloonning
Summary and Plans (III)

• I-mode
  – Clear demonstration of $\chi_{\text{eff}}$ suppression correlated with vanishing 60—150kHz edge turbulence
  – WCM at 200—300kHz observed in B, n and T fluctuations
  – New information coming to light about amplitude of flucfs in various quantities, poloidal distribution of fluctuations
  – Correlation of particle flux with WCM amplitude
    • (A. Dominguez, PhD work)
  – Working on stability analysis with ELITE; May be a good candidate for simulation with GK codes
  – Recent studies of power thresholds for L-I, I-H and I-L transitions helping to clarify and extend thresholds, I-mode operational space
    • (Hubbard, 2011 H-mode Workshop)
  – Expanded power and density ranges planned for FY12
Report on C-Mod Research Goal:
Hybrid Advanced Scenario Investigation

C-Mod Quarterly Review
October 27, 2011
MIT PSFC

Presented by A. Hubbard,
on behalf of C-Mod team
Hybrid Advanced Scenario
Investigation

Text of research goal, from C-Mod work proposals:

With the implementation of Lower Hybrid RF for current profile control, and active cryopumping for density control, C-Mod will investigate advanced scenarios for improved performance of the tokamak. Investigations into the so-called “hybrid” mode of operation, being considered as one possible advanced approach for ITER, will be carried out to evaluate the potential to maintain central safety factor near or slightly above 1 and to assess the effects on plasma transport and confinement.

First proposed in 2007. Initial results in 2008, with LH1 launcher. Completion deferred until FY11 to allow experiments with LH2 launcher.
What is “hybrid scenario”? Why study on C-Mod?

• “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 $q_{95}=4$, $q_{\text{min}} \sim 1$, $\beta_N=2.8$, obtained on D3D, AUG, JET, via H&CH (mainly NBI) in current ramp.

• 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 CD, rather than relying on MHD effects?

• What are roles of $q(r)$ vs $\beta_N$ in confinement improvement?

• Obtained on D3D, AUG, JET, via H&CH (mainly NBI) in current ramp.

• 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 $\beta_N > 2$.

  • C-Mod is well placed to answer these!
  • Hybrid scenario on C-Mod would contribute to several ITPA IOS &TC experiments, databases.
Research Goal a challenging target for integrated scenarios.

The research goal was established as a challenging target for integrated hardware and scenario development using Phase 1 of LH system. Full completion requires:

1. Combination of high power LHCD and ICRH.
2. Density control in H-modes, to make plasmas accessible to LH waves.
3. Coupling of LHCD into H-modes.
4. Efficient LHCD in H-mode plasmas – sufficient to modify core current profile.
5. Measurement of current profile changes.
6. Assessment of transport and confinement with modified shear.

Bottom line:

- We succeeded in 1-3, integrating LHRF, ICRF and cryopump.
- Unexpected new LH physics reduced efficiency (4), preventing completion of 5 and 6.
- Also discovered some new and beneficial effects of LHCD on H-mode pedestal density and energy confinement.
First attempts in 2008 already produced interesting results.

- Collaboration with G. Sips (EFDA) through ITPA.
- Adding LH power in current ramp did delay sawteeth into flat top, indicating higher q(0).
- Then added ICRF, produced H-mode. Combining two RF systems worked well.
- BUT, sawteeth returned soon after ICRF and before L-H transition, first indication that LH current drive was not sustained.
Differences in H-mode pedestals and transitions were seen in LH-modified plasmas.

- With ohmic, sawtoothing targets, prompt L-H transitions within ~ 20 ms (about $\tau_E$) of ICRH turnon.
  - Expected since $P_{\text{ICRF}} \sim 3 \times P_{\text{thresh}}$.
  - Immediate, strong, rise in density.
- In LH-modified (small or no sawtooth) discharges, L-H transition is delayed, occurs 60-70 ms after ICRF.
  - Slower density rise after transition.
  - Generally higher peak $T_{\text{edge}}$ in the H-mode which correlates with higher peak stored energy.

Hubbard, APS 2008
LHCD coupled into steady H-modes, had unexpected benefits

- Developed reduced $n_e$, steady H-mode targets for LHCD, using configuration optimization & cryopumping
  - $n_{e,\text{bar}} = 2 \times 10^{20} m^{-3}$
  - $n_{\text{ped}} = 1.7 \times 10^{20} m^{-3}$

- LH coupling proved if anything better than in L-modes with ICRF.

- Upon adding LHCD ($N_\parallel = 2.3$), observed a further reduction in global $n_e$ and $P_{\text{rad}}$

- Other effects included:
  - Increases in both edge and core $T_e$
  - Strong decrease in $V_{\text{loop}}$
Effects of LH waves on pedestal

- Further studies with pedestal and SOL diagnostics show a consistent decrease in pedestal $n_e$, increase in $T_e$.

- Also prompt increase in SOL density, changes in $I_{sat}$, emissivity indicating edge effects. J.W. Hughes et al, Nuclear Fusion 50 (2010).
  
  - Has attracted interest as a pedestal control tool, part of new ITPA JE (PEP-22).

- Less clear whether changes were due to current drive or something else?
Benefits of LHCD in H-mode were confirmed in 2011 using LH2, at higher ICRF power and performance.

- 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.

600 kA, 5.4 T, 3 MW ICRH, 0.8 MW LH
$\beta_p$ up to 1, 20% bootstrap, $V_{\text{surf}}$ 0.2-0.3
How much LH current is driven in H-modes??

- The changes of density and temperature in H-modes with LH power complicate the assessment of current drive.
- Decreases in $V_{\text{loop}}$ and $I_i$ can be partially due to $T_e(r)$.
- MSE requires a steady background plasma to do baseline subtraction.
- Even Hard X-Ray response can be affected, since detector is apparently also sensitive to neutron-induced gamma radiation.
- Identifying a potentially small amount of $j_{\text{LH}}(r)$ unambiguously is difficult, perhaps impossible.

- Assessment of LHCD in H-modes has been strongly informed by our experiments in high density L-modes, and by modeling – both of which have made great progress in the past few years.

Reported at other quarterly reviews – will summarize here.
Original LH models predicted substantial current drive, far off axis

- Ray Tracing + Fokker-Planck code CQL3D-GENRAY, *without* SOL effects, for 2008 H-mode with cryopumping, predicted good CD as long as $N_{||}$ kept above accessibility limit.

- BUT, LH experiments at end of 2008 campaign (in L-mode) showed strong reduction at $n > 10^{20}$ m$^{-3}$.

- Motivated upgrades to the model which showed the decreases could be largely explained by collisional (or other) losses in the SOL.
  - Including SOL in GENRAY-CQL3D reduced predicted current drive to ~ 20 kA!

Simulation of 600 kA, $N_{||}$=2.3 H-mode discharge, *without* SOL effects, predicted $j_{LH} \sim$ 100 kA.

![Graph showing current density vs. $\sqrt{\psi_{tor}}$]
H-mode densities are in range where SOL effects have been found very significant.

Experiments and simulations with ohmic L-mode targets, 5.4 T, 800 kA, $N_{//}=2.3$.

Up to $4 \times 10^{20}$ m$^{-3}$.

Details in G. Wallace, PoP 17 082508 (2010), Nucl. Fusion 51 (2011) 083032 and multiple C-Mod conference papers.
2011 experiments and modeling confirm low LHCD in H-modes

- Analyzed the high performance H-modes with LHCD shown earlier.
- As noted, HXR dominated by neutron-induced effects; have done first order correction (with high uncertainties).
- Find non-thermals may be higher than in cold L-modes, but are still quite low.

- CQL3D-GENRAY, with realistic SOL profiles, predicts 25 kA LHCD, peaked at r/a=0.9.
- Predicted HXR emission is consistent with experimental estimates.
Implications for “hybrid advanced scenario investigation”

• The current assessment of LH efficiency in C-Mod H-modes, both experimental and simulations, is that only \( \sim 25 \) kA of current drive, far off axis, is likely to be driven with currently achieved plasma parameters, using the present LH system.

• This would produce a change to \( q(r) \) which is too small to be measured with confidence, to raise \( q(0) \) above 1, or likely to affect core transport and stability in steady conditions. Changes in \( q(r) \) before H-modes were produced, so it is possible there may be transient effects.

• Our original goal of evaluating \( q(r) \) effects on H-modes, and producing “hybrid scenario” via LHCD, thus seems unlikely to be feasible.

• We have however observed other, new and unexpected, effects of LH waves on H-mode pedestals and confinement which are of the same order as those we were aiming to study, and are not yet understood. May well be related to SOL wave absorption and ‘density limit’.
Future research plans

• While we consider the assessment for this Research Goal complete, will **continue research aimed at understanding and ameliorating the LHCD reduction at high density.** Top priority for the LH program (as recommended by PAC).

• Promising avenues of research include:
  – Increasing core temperature and single pass absorption, shown in simulations and initial experiments (end of FY10 campaign) to raise HXR at given density.
  – Considering change in poloidal location for LH3.
  – New diagnostics to measure waves, edge parameters.

• In parallel, will **work to develop target advanced scenarios at lower density and higher $T_e$.** I-modes, with H-mode energy confinement but lower density, are promising in this regard. Lower $I_p$ and ELMy H-modes will also be explored (though coupling to asymmetric shape may be challenging).

• Continue **to investigate LH wave effects on pedestal**, and explore effects on ELMs – potentially of interest to ITER as control tool.
Rotated ICRF Antenna

Presented by S. Wukitch
Rotated ICRF Antenna

Rotate antenna structure 10° to be perpendicular to total B field.

- Along a field line $E_\parallel$ will cancel due to symmetry and is expected to reduce impurities.

If new antenna achieves $\sim10$ MW/m² (present limit), the injected power will be limited to 2 MW.

- For present J antenna, 3 MW is typical maximum injected power.
- Will need to achieve $\sim15$ MW/m² to achieve 3 MW.

Similar vacuum spectrum as present J antenna.

To reduce impurities, present non-field aligned antennas are operated in dipole [0, $\pi$] phasing rather than monopole phasing [0,0].

- Estimated integrated $E_\parallel$ is reduced by 2-3.

For an antenna $\perp$ to the total B-field, the integrated $E_\parallel$ is expected to be reduced.

- For [0, $\pi$, 0, $\pi$], estimated sheath field is reduced $\sim$3-10.
- Some symmetry breaking prevents $E_\parallel$ from vanishing.
- For [0,0,0,0], sheath field is negligible.
Antenna is Installed

During installation in August, we found the vessel wall deformation was larger than design could accommodate.

- Antenna was ~7 mm in front of the GH limiter.
  - Original design could accommodate 1.5 mm.
- Used the CMM measurements of the wall to establish new back plate radius.
  - HJ wall differs from JK wall.
  - Each back plate has slight different radius.
  - Use picture frame shims for fine positional adjustment.
- Machined radius is 105.54 cm and 105.41 cm for the plates.
- CMM inspection found mating surface between back and center plates was tapered.
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Advanced Machining, Inc. machined and inspected the back plates.

• Antenna assembly was significantly improved.

Installation was delayed 2 months.

• Target installation date was 8/31 at previous quarterly.
Antenna is Positioned well within Tolerance

CMM inspection has found that the antenna is out ~0.5 mm (further away from the plasma).

- Inspected the plasma limiters at GH and K.
- Antenna protection limiters are ~4 mm behind GH limiter.

Diagnostics have been installed.

- Thermocouples, I and V probes have integrated into the antenna.
- SOL reflectometer on H side of rotated antenna.
Assembled Antenna
Antenna Characterization Plan

We will begin by operating at 78 MHz in $(0,\pi,0,\pi)$ configuration with $(0,0,0,0)$ phasing available.

- We will begin by operating into vacuum to investigate voltage limits in vacuum.
- First plasma operation will be to investigate voltage and power handling.
- Examine neutral pressure limit.

Once the H fraction is reasonable, we should characterize plasma response and compare with D and E antennas.

- Investigate plasma response as function of antenna phase, plasma current and density.

Already pursuing modifications/different materials to raise voltage/power handling.

- Modify bridge section and strap grounding – feedthru congestion.
C-Mod Status

DoE Quarterly Review
10/27/2011
Outline

• Status
  – C-Mod
  – ICRF Systems
  – LH Systems
  – Diagnostics/List of Up-to-Air Activities
  – Outer Divertor
• ARRA Upgrades
• Plans and Schedule
C-Mod Status
C-Mod Status

- 14.5 weeks of research operation in FY11, out of 15 week target (97%)
- In-vessel work
  - Installed new rotated ICRF antenna
  - New Lower Hybrid limiter
  - Installation of new diagnostics
- Routine maintenance of power systems
- C-Mod pump down week of 10/31/2011
ICRF Systems
ICRF Systems

- Primary ICRF facility upgrade: installation of the new rotated antenna
- CMM arm used in vessel to verify component locations
  - Horizontal flange, feedthroughs, and strip lines installed
  - Back and center plates, shims, current straps, Faraday shields installed
- In-vessel installation complete (10/27/11)
Fast Ferrite Tuner Specifications

Fast Ferrite Tuner (FFT) is a shorted, ferrite loaded strip line where the electrical length is controlled by an applied magnetic field.

Design is similar to the FFTs utilized on E antenna.

- Improved the power handling for 5 seconds and
- Increased the differential phase at 50 and 80 MHz.

We plan to run dynamic tests on first pair of tuners in early December at AFT in Backnang, Germany.

Frequency 50-80 MHz

Differential phase > 90° at 50 and 80 MHz at room temperature

Tuning speed > 4 ms (10%-90% rise time)

Pulse length 5 s

Time between pulses 1200 s

Voltage standoff 40 kV

Circulating Power 5 MW
Ferrite Tuner Schematic

Permanent magnet

Electromagnet

Cooling connection

Ferrite loaded strip line

Iron Yoke

Short

Coax to strip line transition
Ferrite Tuner Cross Section

- Electromagnet
- Permanent magnet
- Iron Yoke
- Ferrite loaded strip line
Manufacturing Status

- Inner conductor and outer conductor are the most difficult to manufacture:
  - Cooling structure needs to be plated (completed).
  - Structure needs to be brazed (incomplete).
  - Ferrites need to be attached (incomplete).
Lower Hybrid Systems
Lower Hybrid

- Primary lower hybrid efforts over last quarter
  - Installation of the transmitter protection system (TPS)
  - Fabrication of 4th cart
  - Mods to LH limiter

TPS Control Board
SBIR Phase I and II

4th Cart Layout
Filament Control
Lower Hybrid

- Fabrication of 4th cart and cart upgrades
  - Allows full 4 MW source power
  - Acceptance tests of new filament supply and control electronics successfully completed
- TPS
  - Control boards in-house
  - Interface programs being written and tested
  - Carts stripped of old equipment
  - New cabling and fiber optic links being installed
- LH limiters now attached to the launcher --- Maintain spacing between launcher and limiter as launcher is moved radially
Lower Hybrid

- Third Lower Hybrid Launcher (LH3)
  - Simulations indicate that moving launcher up in port greatly improves performance at high density ---- also indicates synergistic operation with current launcher (LH2)
  - Experiments during FY2012 with new limiter configuration will help determine if new launcher can be installed in the D-Port Horizontal port without affecting E-Port ICRF antenna operation
  - We are proceeding with a new above mid-plane design
Diagnostic Changes During Up-to-Air Period
Diagnostics

- **CECE**
  - Measurement of fluctuations/correlations in $T_e$
  - Measurement critically dependent on plasma volume viewed
  - Installed and aligned in-vessel
- **New AXUV detectors at six locations**
  - Toroidal asymmetries during disruption mitigation experiments
  - Installed in-vessel
- **Radio Frequency Quadrupole Accelerator**
  - Deuterium bulk retention and depth profiles
  - Boronization layer thicknesses
  - Erosion rates
  - Isotopic analysis of material composition
  - Beam operating in lab with new control system and data acquisition
  - Mods to B-Hor flange for RFQ accelerator and HXR detector --- complete
Diagnostics

- QCM Antenna (replaces active MHD antenna)
  - Active probing of QCM (EDA H-mode), WCM (I-mode)
  - Excitation of edge modes
    - Installed and aligned
- Fast Ion Loss Detector
  - Measure ICRH tail ion losses
  - Resolve high frequency MHD activity
    - Installed
- 2nd swept reflectometer
  - Edge density near new rotated ICRF antenna
    - Fluctuations
      - Waveguides installed
- Polarimetry from one to three chords
  - Constraints to EFIT
    - Three chords operational
- Spectroscopic fiber array at A-Hor --- installed
- Replace/refurb inner wall tiles --- complete
- Repair/refurbish/relocate flux and $B_p$ loops - complete

Turning mirrors
Diagnostics

- Fast gas injection at F port
  - Increase disruption mitigation capability (2’nd toroidal location)
    - installed
- New MSE shutter and in-situ calibration system
  - Resolve calibration drift issues
    - Installed/tested/calibrated
- Upgrades to outer and inner divertor probe, TC, calorimeter systems
  - complete
- K-port limiter moved out in major radius by 2 mm
  - Reduce damage to limiter
    - Distribute power on other limiters
    - complete
- New x-ray tomography box between C&D ports
  - Improved reconstructions
    - complete
- Impurity seeding gas lines at B and H ports
  - complete
List of Up-to-Air Activities

- post-run calibrations
- new rotated antenna installation
- CECE
- new LH limiter
- 2\textsuperscript{nd} disruption gas jet
- Fast Ion Loss diagnostic
- ICRF SOL reflectometer
- Vertical scanning probe
- A/K upper divertor probes
- GH limiter Thermocouples
- QCM antenna/limiter
- AXUV diode array for disruption diagnostic
- CXRS periscope mods
- Impurity spectroscopy refurbishment
- Impurity seeding feed line installation
- 5\textsuperscript{th} X-Ray tomography array

- replace G-Hor port extension ---- better entry access
- mods to bolometry arrays
- replace/repair flux loops
- relocate B\textsubscript{p} coils (away from antenna location)
- replace Thomson scattering viewing dump
- MSE in-situ calibration system
- Refurbishment
  - Clean LH windows
  - Clean all optical windows
  - Check and exercise shutters
  - Replace polar retroreflectors
- New 50 Hz Thomson Scattering lasers (10/31 to 11/04 commissioning)
- ITER Grounding Test (10/24 to 11/04 installation)
- Polarimeter upgrade from one to three chords
- Mods to B-Hor flange for new diagnostics and RFQ beam
- pre-run calibrations
Outer Divertor Upgrade
Outer Divertor

- Status
  - Design of divertor components moving along
  - Major outstanding issues
    - Testing of heater concept/design
    - Current shunt design
    - Spherical bearing design for A-Frame support
    - Diagnostic access
  - A successful peer review of the C-Mod divertor upgrade installation and assembly procedure was held on 9/28/11 at PPPL
    - Detailed plan for assembly was presented
    - Special focus was given to positioning divertor to within tight tolerance spec
    - Alignment fixtures and tool access were discussed
    - A few of the over 100 slides in the assembly sequence follow
Outer Divertor

Starting with existing vessel
Outer Divertor

Install A-frames

Spherical Bearing
Outer Divertor

Install outer divertor ring

heaters

W tiles
Outer Divertor

Install top plates
Outer Divertor

Install floor plates
Outer Divertor

Install EFI heat shield supports
Outer Divertor

Install EFI heat shields
Outer Divertor

Install dome

End of Sequence
ARRA Upgrade Status

- We have $5.439 M committed of 5.895 M in funding
- Remaining $0.456 M will be used to
  - Fabricate 2\textsuperscript{nd} Advanced ICRF Antenna
  - Complete 4\textsuperscript{th} cart and ICRF FFT systems
Near Term Operations Plan and Schedule
Near Term Operations Plans

- Pump-down week of 10/31/2011
- Begin FY2012 research operation Dec 2011
  - 17 research weeks, including
    - Operate of new antenna
    - Investigate LH coupling and density limit
    - Core transport (JRT)
- Completion of Lower Hybrid Transmitter Protection System (TPS) by January 2012
  - Currently have administrative limit of 0.5 s for the lower hybrid pulse length
  - TPS will allow extension of pulse length to <5 s
Operations Schedule

- Pump-down week of 10/31/2011
- No maintenance weeks are shown, but are being considered
  - Install/commission new diagnostics
  - Complete TPS system
APS-DPP Presentations

• Invited Talks
  – Nathan Howard: Measurement and Gyrokinetic Simulation of Impurity Transport in the Core of Alcator C-Mod
  – John Rice: Rotation Reversal and Energy Confinement Saturation in Alcator C-Mod Ohmic L-mode Plasmas: A Novel Transport Bifurcation
  – Catherine Fiore: Production of Internal Transport Barriers via self-generated flows in Alcator C-Mod
  – Earl Marmar: Pedestal and Transport Properties of Steady-state I-mode Plasmas over Expanded Operational Space in Alcator C-Mod
  – Greg Wallace: Lower hybrid current drive at high density in the multi-pass regime
  – Phil Snyder: The EPED Pedestal Model: Gyrokinetic Extensions, Experimental Tests, and Application to ELM-suppressed Regimes

• 20 Contributed Orals (including 5 in special ITER session)
• 38 Contributed Posters