Overview of Alcator C-Mod Research Program

S. Scott for the C-Mod team

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Explore a range of physics issues of interest to ITER in ITER-like regimes

- Magnetic field
- Plasma density and pressure
- Equilibrated ions / electrons
- High-Z PFCs
- Power density in SOL
- Divertor opacity to neutrals and radiation
- Momentum input and fueling decoupled from heating and current drive

Topics

- Performance with all-metal walls and physics of 'boronization'
- Initial results with Lower Hybrid Current Drive
- MHD studies: disruption mitigation, locked modes
- Alfven Cascades
- Turbulence measurements & simulations (TEM)
- Scaling of 'intrinsic' toroidal rotation
- The plasma edge: SOL transport, 'blob' dynamics, ELMs
Extensive Campaign to Characterize Performance with All-metal walls and Effect of Boronization

Motivation:
- ITER $\tau_E$ projections are based mostly on confinement expts with low-Z PFCs or low-Z wall coatings (Li, Be, B).
- $W$ chosen for ITER based on hydrogen retention, neutron damage, etc. despite low allowable concentration (~$10^{-4}$).

C-Mod (< 2005) Mo walls, overnight boronization since 1996; BN tiles in 2000

CY 2005-06 campaign
- Removed boron from PFCs (~10% left).
- Removed BN tiles
- Extended campaign with all-metal PFCs.
- Then compare to overnight or between-shot boronization.

Result: consistently higher performance with boron: Lower $P_{\text{rad}}$, lower $n_{\text{Mo}}$, higher $W_{\text{tot}}$. Record tokamak $\langle p \rangle = 1.8 \text{ atm at } \beta_n = 1.74$. 

Marmar, EX/3-4
Performance with all-metal (Mo) PFCs is limited by radiation from molybdenum impurity

- H-modes readily achieved with all-metal PFCs, but $P_{\text{rad}}$ is high and $H_{89p} < 1.3$.
- Overnight boronization (200 nm) reduces $n_{\text{Mo}} > 5x$.
- Lower $n_{\text{Mo}}$ reduces $P_{\text{rad}} \Rightarrow$ increases power flow through SOL $\Rightarrow$ pedestal pressure increases.
- Profile 'stiffness' propagates increased $P_{\text{ped}}$ to improved global $\tau_E$.
- Favorable effects wear off in 20-50 shots, or $\sim 50$ MJ deposited RF energy.
- Enhanced sheath potential by ICRF at specific locations is identified as cause of boron erosion and impurity generation.

Marmar, EX/3-4, Wukitch, FT/1-6
Significant D retention is observed with all-metal PFCs.

Retention a function of plasma density but not plasma regime.

Whyte, EX/P4-29
Significant D retention is observed with all-metal PFCs

Retention in C-mod is not caused by co-deposition with boron

- Similar retention rates observed with all-metal versus boronized PFCs: 20-40% of fuelled gas, ~0.5% of incident ion flux.

- DIONISOS facility will expose Mo target to high-flux, low-energy D plasma to study retention & saturation.

Whyte, EX/P4-29
Major goal of C-Mod program is to study LHCD and its application to high performance integrated AT Plasmas

Objective: inform decision on LHCD for ITER & enhance prospects for ITER's hybrid and steady-state operations.

- measure LH coupling, current-drive efficiency, control of j(r)
- benchmark LH codes (GENRAY/CQL3D) used to model proposed AT regimes for ITER.

LHCD system: 3.0 MW (source) 
\(n_{||} = 1.5 - 4.5, 4 \times 24\) grill

Accome modeling of LHCD indicates fully steady-state, high-performance regimes are accessible
Initial LHCD results are promising: $V_{\text{loop}} \sim 0 \text{ V}$ at $I_p = 1.0 \text{ MA}$ for $\sim 200 \text{ ms}$ at $I_p = 1.0 \text{ MA}$

$P_{\text{LH}} = 800 \text{ kW}$, $60^\circ$ phasing, $n_{||} = 1.6$, $\tau_{\text{CR}} \approx 100 \text{ ms}$

- Reflection coefficients agree with Brambilla code assuming $\sim 1 \text{ mm}$ vacuum gap.
- No evidence of anomalous impurity influx.
- Sawteeth stabilized.
- Measurements of x-ray spectra and emissivity profile agree qualitatively with expectations.
LH current drive efficiency determined from power scaling is favorable

- All shots with 60° phasing, $n_{||} = 1.6$.
- $P_{LH} = 120 - 830$ kW.
- Efficiency: $n_{20} IR/P_{LH} \approx 0.28$
- Efficiency consistent with Genray-CQL3D modelling and ~30% above Accome.
  $\Rightarrow$ promising for future AT studies.

Loop voltage reduction versus normalized $P_{LH}$

- $I_p > 700$ kA
- $\bar{n}_e = 3.5 - 7 \times 10^{19}$ m$^{-3}$

Bonoli, IT/P1-2
Disruption mitigation via gas jet injection shows promise for ITER even at high plasma pressure

- Technique (DIII-D): inject massive amount impurity gas to radiate $W_{\text{tot}}$ isotropically during disruption. $P_{\text{rad}} \sim 1 \text{ GW}$ needed in C-Mod.

- Extend mitigation to ITER-like plasma pressure (these expts $\langle p \rangle = 0.8 \text{ atm}$, ITER = 1.75).

Radiated energy fraction increases with $Z_{\text{gas}}$, reaching ~80-90%.

Halo currents reduced ~50%.

Divertor tile heating reduced ~60%.

- Gas mixture (90% He, 10% Ar) obtains favorable radiative properties of high-$Z$ with rapid transit of helium through gas delivery system.

Granetz, EX/4-3
NIMROD MHD simulations show edge cooling triggers 1/1, 2/1 tearing modes, leading to stochasticity

- In both DIII-D and C-Mod, high-speed imaging of gas jet plumes shows that impurity neutrals do not penetrate past plasma edge.

- Nevertheless, energy throughout plasma is radiated in 1-2 ms. How?

- NIMROD: growth of 1/1, 2/1 \rightarrow stochastic field lines \rightarrow core energy transported to edge \rightarrow radiated by impurities.

- Favorable for ITER: direct penetration of neutral gas is not necessary.
B_T Scaling of Error Field for Locked Modes
Implies a Radius Scaling Favorable for ITER

Parameterization of locking threshold:

\[ \frac{\tilde{B}}{B_T} \propto n^{\alpha_n} B^{\alpha_B} q^{\alpha_q} R^{\alpha_R} \]

- Scaling of \( \tilde{B} / B_T \) locking threshold is needed to extrapolate to ITER.

\[ \alpha_n = 1 \text{ (experiment)} \]
\[ \alpha_R = 2\alpha_n + 1.25 \alpha_B \text{ (Connor-Taylor)} \]

- C-Mod expt: \( B_T \) scan with \( n \propto I_p \propto B_T \),
\( n/n_G = 0.17, q_{95} = 3.5, \tilde{B}_{11}/\tilde{B}_{21} = 1.4 \).

- C-Mod data implies \( \alpha_R = 0.68 \pm 0.19 \) and projects to \( \tilde{B}_{21}/B = 0.9 \times 10^{-4} \) at ITER's ohmic density (within ITER design constraint).
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- JET/C-Mod identity experiments: JET shape, \( \tilde{B}_{11}/\tilde{B}_{21} = 2.1 \). Confirms Connor-Taylor & \( \alpha_n = 1 \).
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- Caveat: Lower-field (4 Tesla) C-Mod locking threshold using the JET shape might imply a less favorable R scaling to ITER.

- JET/C-Mod identity experiments: JET shape, \( \tilde{B}_{11}/\tilde{B}_{21} = 2.1 \). Confirms Connor-Taylor & \( \alpha_n = 1 \).
Scaling of intrinsic plasma rotation in H-mode from multiple tokamaks provides guidance for $V_\phi$ in ITER

$V_\phi \propto \Delta W/I_p$ in individual tokamaks, but size scaling is evident

Results unified in plots of $M_i = V_\phi/C_s$ or $M_A = V_\phi/V_A$ versus $\beta_N$.

Parameter range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.21 - 1.2 m</td>
</tr>
<tr>
<td>R</td>
<td>0.67 - 3.4 m</td>
</tr>
<tr>
<td>B</td>
<td>1.4 - 5.4 Tesla</td>
</tr>
<tr>
<td>I_p</td>
<td>0.3 - 3.0 MA</td>
</tr>
<tr>
<td>W_p</td>
<td>0.04 - 4.0 MJ</td>
</tr>
<tr>
<td>$V_\phi$</td>
<td>30 - 130 km/s</td>
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- No apparent correlation of $V_\phi$ or M with $\nu^*$ or $\rho^*$.
- Inferred scaling with $\beta_N$ projects to $M_i = 0.3$ or $M_A = 0.02$ for ITER at $\beta_N = 2.6$, $V_\phi = 250$ km/sec, probably sufficient to stabilize RWMs.

Rice, EX/P3-12
Internal transport barrier (ITB) generated by off-axis RF heating, controlled with on-axis RF.

- On-axis heating increases $T_e \Rightarrow$ drives strong TEM in ITB. TEM limits electron density gradient and explains control of ITB with on-axis ICRH.
Observation of TEM turbulence in tokamaks

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- Nonlinear GS2 gyrokinetic simulations with new synthetic PCI diagnostic reproduce:
  - wavenumber spectrum with on-axis ICRH.
  - increase in density fluctuation level with on-axis ICRH.

Ernst, TH/1-3
Nova-K with synthetic PCI diagnostic improves understanding of Alfven cascades

Phase Contrast Imaging (PCI) observes 'chirping' with multiple modes

Alfven cascades produced by early ICRF when q(r) reversed, $q_{\text{min}} = 2$. 

Porkalab, EX/P6-16
Nova-K with synthetic PCI diagnostic improves understanding of Alfven cascades

Nova-K calculations including GAMs reproduce measured frequencies

Chirping behavior is sensitive to q(r,t). Agreement with Nova-K indicates plasmas have RS.

Multiple peaks radially observed

- Caused by multiple peaks in the actual radial mode structure, on artifact arising from integration along PCI sightlines?
- Synthetic PCI 'diagnostic' in NOVA-K indicates that multiple peaks consistent with a single radial mode.
Transport scaling near the separatrix is consistent with electromagnetic fluid drift 3-D Turbulence

- Theory: Turbulence & transport is controlled by two dimensionless parameters
  
  \[ \alpha_{\text{MHD}} \propto q^2 R \frac{\nabla T_e}{B^2} \]  
  
  (inverse) Collisionality:  
  
  \[ \alpha_d \propto \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \left( \frac{R}{L_n} \right)^{1/4} \]

- Experiment: \( \nabla T_e \propto I_p^2 \) applies in both USN and LSN, but LSN achieves higher \( \nabla T_e \) and higher \( \alpha_{\text{MHD}} \). Observed \( \nabla T_e \propto I_p^2 \) scaling consistent with EMFDT.

- Plasma flows are different in USN vs LSN, suggesting flows affect accessible values of \( \alpha_{\text{MHD}} \).
Intermittent turbulent structures ('blobs') at the edge have been measured with high temporal, 1-D and 2-D resolution.

- SOL turbulence affects plasma-wall interaction, sets boundary condition for core plasma.
- Phenomenology important to guide & challenge first-principle models of intermittent transport in SOL.
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Blob flow patterns change across SOL into limiter shadow

Blobs in the SOL have a net outward radial motion with a mean velocity ~1% of $C_s$
Gas-puff imaging also used to study ELM dynamics at high resolution

- High triangularity, low $\nu^*$ (<1) H-modes produce discrete ELMs with $\Delta W_{\text{ped}}/W_{\text{ped}} = 10\text{-}20\%$ per ELM.

- ELM precursor: 200-400 kHz, $n_{\text{toroidal}} \sim 10$ inside separatrix, propagates in ctr-$I_p$ dir'n.
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- Followed by ejection of rapidly propagating 'primary' filaments ($V_R = 0.5 - 8.0$ km/s), radial size 0.5 - 1.0 cm, at time of pedestal crash.

- 'Pedestal' on inboard and outboard sides is perturbed before ejection of filaments.

- 'Primary' is followed by multiple, slower secondary filament ejections.
C-Mod Facility Upgrades 2006-8

- Toroidal cryopump → density control in AT
- Tungsten belt in divertor → long pulse, high power
- 2nd LH launcher → 4 MW (source), compound spectra
- 2nd 4-Strap RF antenna → make room for LH
- Fast ferrite RF tuners → 1 ms response, tune thru ELMs
- Rotate DNB 7° → resolve MSE calibration issues
Summary

- Results favorable for ITER
  - disruption mitigation
  - LHCD
  - scaling of locked modes
  - scaling of intrinsic rotation

- Potential issues for ITER
  - plasma performance without low-Z PFCs or coatings
  - hydrogen retention in moly - worry for tungsten also?
  - erosion and impurity generation by RF sheaths

- Progress in physics basis for ITER
  - plasma edge understanding: pedestal transport, SOL transport, 'blob' dynamics, ELM dynamics
  - Role of TEM in electron transport clarified
  - Alfven Cascade - radial structure