Overview of Experimental Results and Code Validation Activities at Alcator C-Mod

IAEA Fusion Energy Conference
San Diego, October 8, 2012
M. Greenwald - presenting for Alcator Group
This talk will address the unique capabilities of C-Mod for validating physics relevant to ITER

- All metal walls and reactor-like heat fluxes
- RF scenarios at ITER $B_T$, $n_e$, RF frequencies
- Transport studies without core particle or momentum sources
- RF actuators
- Core Transport
- Pedestals and Edge Barrier Physics
- Boundary Plasmas/Plasma Wall Interactions
- Disruptions
An Innovative ICRF Antenna Has Been Developed To Address The Issue Of Metallic Impurity Generation

- Critical issue for metal machines like ITER
- Hypothesis: RF sheath rectification and acceleration of ions into wall
  - Large RF potentials measured far from antenna (*EX/P5-39 Terry*)
- Antenna designed to minimize $E_\parallel$
- Results:
  - Improved RF power handling
  - Reduced Mo radiation
  - Discrepancies with models remain

Field Aligned Antenna

Standard Antenna
Experiments to validate full-wave ICRF heating simulations (TORIC/AORSA/CQL3D)

- Compare to fast ion spectra
  - Generally there was good agreement with the equilibrium fast ion population and scaling with $I_p$ and $P_{ICRF}$
  - Disagreement on transient formation and decay of the fast ions levels
    - (Bader NF 2012)

Comparison to RF waves in plasma (PCI)

- Agreement in Minority heating regime
- For mode-conversion regime, measured wave intensity was 50x lower than code
- Is this evidence for nonlinear effects?
  - (Tsujii PoP 2012)
LH Is An Efficient Current Driver
At The ITER $B_T$, Density and RF frequency

- 100% non-inductive plasmas have been achieved at 5.4T, $5 \times 10^{19}$
  - Modification of current profile leads to formation of an internal transport barrier
- At higher density ($>1 \times 10^{20}$), driven current and fast electron populations drop below simple predictions
  - Not linear wave accessibility issue

Full wave (LHEAF/VERD) FE and ray tracing models (GENRAY) find that large fraction of wave energy propagates in plasma edge and SOL at high densities
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Mechanisms connected to low single-pass absorption

- High-frequency probe measurements find evidence of PDI on high-field side
- Collisional wave damping in edge
- Loss of fast electrons created near plasma edge

Solution is to run with higher single-pass absorption (as ITER will)

- Higher $T_e$ and/or change in poloidal location of launcher
- Additional poloidally displaced launcher is planned
Core Impurity Transport – Validation of Gyrokinetic Model

- Impurity transport studied using LBO method – well defined, non-intrinsic source
  - Time-dependent Ca\textsuperscript{18+} brightness profiles measured with x-ray-imaging
  - STRAHL used in iterative loop to determine experiment D,V profiles and experimental uncertainties
- GYRO used for nonlinear modeling and sensitivity studies
- Simultaneous agreement achieved for ion heat and impurity D and V; but not with electron heat transport
  - Extension of simulations to higher k modes does not solve discrepancy
- Parallel impurity transport theory extended to account for ICRF fast ions – agrees with observed poloidal impurity density asymmetry

\textbf{EX/P3-23 Howard}
\textbf{EX/P3-01 Reinke}
Transport Explored at Transition Between Electron and Ion Dominated Transport

- For OH discharges - simultaneous changes in
  - Energy confinement scaling; electron to ion dominated transport
  - Disappearance of higher freq. density fluctuations, $T_e$ fluctuations
  - Flow reversal at $q \approx 3/2$ surface
  - Non-local to local heat transport
  - Edge impurity asymmetry

- In L-mode, self-generated rotation profile transitions from peaked to hollow as $n_e$ goes from 1 to $1.2 \times 10^{20}$ (at $I_p = 0.8$ MA)
  - Correlated change in momentum and impurity pinch velocities (but with opposite signs)
  - Transition is not at the predicted linear-gk ITG/TEM boundary.

- Ohmic phenomena occur at $q$ dependent, critical density (or $v^*$ at $q \approx 3/2$) $EX/2-2$ Rice
Thresholds and Pedestal Structure
Critical Extrapolations for ITER

- L-H power threshold
  - Density dependence is unlike power-law fit derived from multi-machine scalings
  - Threshold minimum scales with $B_T$ (not $I_p$ or $q$)
  - Significant drop in threshold power for “slot” divertor – effect of long divertor arm
  - Testing data against local and global threshold models - RDZ/Guzdar/FM$^3$ EX/P2-04 Ma

- Pedestal structure for ELMy discharges
  - C-Mod extends pedestal pressure range
  - Pedestal width consistent with KBM-like, weak $\beta_p$ scaling
  - Pedestal height matches EPED predictions, ELITE stability calculations

EX/P4-15 Hughes; EX/11-4 Groebner
I-mode Provides High Performance Without ELMs Or Impurity Accumulation

- Usually accessed by running at high power with $\nabla B$ drift in unfavorable direction
  - H-mode-like energy transport & $T_e$ pedestal
  - L-mode-like particle transport & $n_e$ profile
- Clear separation of particle and density barriers:
- Lack of ELMs consistent with ELITE modeling

- Encouraging extrapolation to ITER (Q ≈ 10)
  - I-mode is currently a focus of multi-machine studies (ITPA)
  - Need more information on density, power and size dependence for access

EX/1-3 Hubbard; EX/P4-22 Lin; EX/P4-15 Hughes
Short Wavelength EM Fluctuations Seen in Alcator C-Mod May Regulate Profiles in Edge Barriers

- **Weakly Coherent Mode in I-mode**
  - (200-300 kHz, $\delta f/f \approx 20-100\%$, $k \approx 1.5$ cm$^{-1}$)
  - Particle diffusivity scales with WCM amplitude
  - Energy barrier associated with drop in lower frequency fluctuations

- **Fluctuations between ELMs in ELMy H-mode**
  - (250-550 kHz, $\delta f/f \approx 30\%$, $k \approx 0.6-0.7$ cm$^{-1}$)
  - Amplitude increases as profiles recover between ELMs
  - Evidence for predicted Kinetic Ballooning Mode?
LH Waves Offer Possibility For A Pedestal and Confinement Control Tool

- Strong change in profiles, transport
  - Increase in $T_e, T_i$ - Drop in $n_e$
  - 30% increase in stored energy
  - Accomplished with 0.6MW LH added to 3MW ICRF

- Order of magnitude drop in edge fluctuations

- Substantial impact, even under conditions where LH waves ($n_{\parallel} = 1.9$) do not have access to the core plasma
“Blob” Analysis Suggests A Unique Opportunity To Validate Edge Turbulence Models

- Generated in near SOL then propagate into far-SOL and to wall
- Data has huge dynamic range measured in event size, and probability
- Blobs show exponentially distributed waiting time and amplitude
- Statistical model developed (Garcia PRL 2012)
- Two numbers completely characterize process
  - Birth duration
  - Average waiting time
- PDFs and their profiles reproduced with high accuracy
Heat Flux Footprint – Connected to Midplane Edge Turbulence

- Midplane pressure maps to divertor and to divertor heat-flux footprint
  - **Width independent of** $B_T$, $q_{95}$, $P_{IN}$ or connection length
- $I_p$ (or $B_p$) is the dominant control parameter (as it is for the pedestal)
- Data at midplane point to dominance of turbulent perpendicular transport - near marginal stability
  - **MHD ballooning parameter**, $\alpha_{\text{MHD}}$ brings wide range of data together
- Implies importance for ratio of pressure gradient length to field curvature length
- Suggests heat footprint will scale with machine size
  - **Apparently inconsistent with multi-machine regression** – must sort out for ITER
Growth of W nano-structures have been observed in PWI test-stands

- Hypothesis: Small filaments “extruded” by helium bubbles captured in metal substrate
- Could be major source of erosion and dust production in future reactor – if process occurs in that environment

Open question: Could these processes occur, undisturbed in operating tokamak environment?

On C-Mod, careful experiments were performed to raise sample to correct temperature range (~2000°K)

- Morphology (tendrils ~100nm) and growth rates (~600nm in 13 sec) match
- Provides confidence that key growth parameters, from linear devices, can be used for prediction in future devices.
Tokamak Plasma-Wall Processes
First Time-Resolved, \textit{in situ} Measurements

- 1 MeV deuteron ion beam installed for time-resolved, \textit{in-situ} measurements of plasma-wall interactions
- reactions exploited:
  - $D + B^{11} \Rightarrow P + B^{12} + \gamma$
    (Measures boron surface coating)
  - $D + D \Rightarrow H e^3 + n$
    (Measures fuel retention)
- Time to make measurement: < 5 minutes
  - Between shots
  - Samples not removed from machine
- Measurements of boron overcoating
  - 5x reduction in boron in 1 run day
- Ability to scan wall poloidally and toroidally demonstrated
Disruption Mitigation – Radiation Symmetry Is A Critical Issue For ITER

- Using massive gas injection, C-Mod observes toroidal peaking factors 1.2-2.3
  - Peaking factor > 2 could lead to local melting on ITER
- Can 2\textsuperscript{nd} valve reduce asymmetry?
- Toroidal radiation symmetry studied with multiple gas valves and array of XUV diodes
- It is possible to reduce asymmetry in pre-thermal quench by careful control of geometry and timing
- BUT.....

- Asymmetry depends on n=1 MHD and thus sensitively on magnetic geometry and $q_{95}$
- More asymmetry seen with faster MHD growth rates
- Modeling underway with NIMROD

\textbf{EX/P8-09 Granetz; TH/P3-13 Izzo}
Future Plans: Further Develop Unique Capabilities

- Deploy hot (1000K), continuous, solid tungsten divertor
- Required for reactor level heat fluxes in C-Mod
- Prototypical for Reactor
Future Plans: Further Develop Unique Capabilities

Exploit capabilities for in-situ measurements of plasma wall interactions
Future Plans: Further Develop Unique Capabilities

Study and Exploit Field-Aligned ICRF Antenna
Future Plans: Further Develop Unique Capabilities

Develop Advanced Off-Midplane LH Launcher

Better single-pass absorption
## C-Mod IAEA Papers/Posters (1)

<table>
<thead>
<tr>
<th>Time</th>
<th>Author</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Monday</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OV/2-3</td>
<td>Greenwald</td>
<td>C-Mod overview</td>
</tr>
<tr>
<td>FTP/1-1</td>
<td>Wukitch</td>
<td>Evaluation of optimized ICRF and LHRF antennas</td>
</tr>
<tr>
<td><em>Tuesday</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX/1-3</td>
<td>Hubbard</td>
<td>I-mode</td>
</tr>
<tr>
<td>EX/2-2</td>
<td>Rice</td>
<td>Rotation reversals, LOC-SOC, and non-local transport</td>
</tr>
<tr>
<td>FTP/P1-22</td>
<td>Wallace</td>
<td>Advances in LHCD technology</td>
</tr>
<tr>
<td>EX/P2-02</td>
<td>Kessel</td>
<td>Modeling of ITER demonstration discharges</td>
</tr>
<tr>
<td>Th/1-1</td>
<td>Murakami</td>
<td>Toroidal flow generation via ICRF minority heating</td>
</tr>
<tr>
<td>EX/P2-04</td>
<td>Ma</td>
<td>H-mode thresholds</td>
</tr>
<tr>
<td>EX/P2-16</td>
<td>Shiraiwa</td>
<td>Steady-state regimes with LHCD</td>
</tr>
</tbody>
</table>
# C-Mod IAEA Papers/Posters (2)

<table>
<thead>
<tr>
<th>Time</th>
<th>Author</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wednesday</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX/P3-01</td>
<td>Reinke</td>
<td>Parallel impurity transport and poloidal asymmetries</td>
</tr>
<tr>
<td>EX/P3-13</td>
<td>Porkolab</td>
<td>Gyrokinetic analysis of Ohmic plasmas</td>
</tr>
<tr>
<td>EX/P3-23</td>
<td>Howard</td>
<td>Gyrokinetic modeling of impurity transport</td>
</tr>
<tr>
<td>EX/P3-28</td>
<td>Fiore</td>
<td>Stabilization of ITBs by self-generated rotation</td>
</tr>
<tr>
<td>EX/P4-14</td>
<td>Delgado-Aparicio</td>
<td>Impurity generated “snakes”</td>
</tr>
<tr>
<td>EX/P4-15</td>
<td>Hughes</td>
<td>Pedestal stability and transport</td>
</tr>
<tr>
<td>EX/P4-22</td>
<td>Lin</td>
<td>NTMs in high-performance I-mode plasmas</td>
</tr>
<tr>
<td><strong>Thursday</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX/P5-03</td>
<td>Wright</td>
<td>Tungsten nano-structures</td>
</tr>
<tr>
<td>EX/P5-39</td>
<td>Terry</td>
<td>Fine-scale SOL Er structure in ICRF heated plasmas</td>
</tr>
<tr>
<td>TH/P6-11</td>
<td>Bonoli</td>
<td>LHCD Modeling</td>
</tr>
<tr>
<td><strong>Friday</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX/P8-09</td>
<td>Granetz</td>
<td>Symmetry of mitigated disruptions</td>
</tr>
<tr>
<td>EX/11-4</td>
<td>Groebner</td>
<td>Multi-machine pedestal studies</td>
</tr>
</tbody>
</table>

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