C-Mod Plasma boundary program

General program description
Transport
Boronization studies
Divertor
D retention in molybdenum
Dust
ITPA contributions
Summary

Presented by B. Lipschultz
Contributions from B. Labombard, S. Lisgo, J. Terry, D. Whyte, S. Zweben & C-Mod group
C-Mod attributes lead to a capability to study important (and probably unique) aspects of edge physics

• 2-8 Tesla magnetic field (ITER 5.3 T)
  ■ High parallel power density (≤ 0.5 GW/m² approaching that of ITER)
  ■ High density
    • Short neutral mean free paths in SOL and divertor ideal for accessing ITER regimes (difficult or impossible for other tokamaks)
      ◆ SOL opacity to neutrals and impurities - affecting fueling and impurity screening
      ◆ Tests of divertor neutral viscosity, i-n and n-n collisions in models
      ◆ Divertor radiation transfer - affecting the ionization/recombination balance and detachment
  ■ Divertor plasma densities spanning that of ITER

• High-Z Plasma Facing Components (ITER Be/C/W initially, all-W later?)
  ■ D/T retention
  ■ Effects of high-Z PFCs on the core plasma and operational experience
  ■ Conditioning experience with high-Z PFCs

C-Mod’s parameters, materials and studies bring breadth to the US (and International) program
C-Mod Boundary physics program emphases

• Combining C-Mod unique characteristics with the goal of advancing the tokamak concept brings emphases on
  - Edge plasma transport
    - Our primary emphasis because it is the determining factor for heat and particle loadings, impurity sources and transport
  - Neutral physics affecting core, divertor and edge plasmas
  - Impurities (sources, effects on core)

  • GOAL: Develop predictive capability scaleable to ITER & reactors

• We also identify and develop hardware and operational techniques in support of advancing the tokamak concept
  - Propose and develop high heat flux handling, particle and impurity control methods
C-Mod boundary transport research has several emphases, rooted in understanding SOL transport

Current transport descriptions are very inadequate, giving rise to large uncertainties in

- Heat load profiles for divertor and walls (and surface lifetime)
- Impurity sources and effect on core plasma
- $T$ retention processes and removal techniques

We need better measures, empirical and physics-based, of transport magnitude/scaling
The SOL appears to have different regions with different transport

- The regions ‘near’ and far from the separatrix exhibit different characteristics
  - Far SOL
    - High turbulence levels, convective transport
    - Transport independent of local parameters
  - Near SOL (one density e-folding length)
    - Less turbulence and less convective
    - Cross-field transport dependent on local $\nu^*$

- Picture emerging
  - Plasma filaments intermittently ‘peel away’ from the edge of the steep-gradient, near SOL region and freely propagate towards the wall.
  - Radial ion fluxes, and wall recycling, CAN compete with parallel flow to the divertor
Far SOL: Blob/filament propagation studies

• Filament size (∥B & ⊥B) and dynamics
  - Several methods utilized
• Scaling and inter-machine comparisons of radial propagation are present emphasis (IEA/ITPA DSOL-15)

• Plans to expand to TJ-II, AUG, DIII-D, JT-60U
• Plans for comparisons of \( v_r \) with theory/modelling ongoing
  - Riso (Garcia/Naulin)
  - Lodestar (Myra/D’Ippolito)

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<thead>
<tr>
<th></th>
<th>NSTX (Zweben)</th>
<th>C-Mod</th>
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<tbody>
<tr>
<td>( B_{edge} )</td>
<td>0.2 - 0.3 T</td>
<td>4.4 T</td>
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<tr>
<td>( n_{edge} )</td>
<td>0.2 - 2x10^{19}/m^3</td>
<td>2 - 20x10^{19}/m^3</td>
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<tr>
<td>( T_{e,edge} )</td>
<td>5-50 eV</td>
<td>20-80 eV</td>
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<tr>
<td>( L_{pol} )</td>
<td>5-9 cm</td>
<td>0.6 - 1.0 cm</td>
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<tr>
<td>( L_{rad} )</td>
<td>2-6 cm</td>
<td>0.7 - 1.5 cm</td>
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<tr>
<td>( V_{pol} )</td>
<td>( \leq 5 ) km/s</td>
<td>( \leq 1 ) km/s</td>
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<tr>
<td>( V_{rad} )</td>
<td>( \leq 1-2 ) km/s</td>
<td>( \leq 1.5 ) km/s</td>
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New studies of ELM dynamics in the SOL

- Precursor oscillation observed - localized in pedestal - growth rate $\sim 1 \times 10^5$/s
- Complex structure observed in a single ELM event
- Collapse in pedestal results in radial propagating “primary” pulse
  - $V_r$ from 0.5 - 8.0 km/s; radial pulse width $\sim 0.5$ cm
  - Reaches wall before divertor
- “Secondary” pulses follow “primary”

**Plans**: compare observations with modelling of MHD stability and ELM dynamics (collaboration w/Leonard, Osborne @ DIII-D)
A number of turbulence studies are planned

• Comparison of blobs in limited/circular plasmas with simulations by B. Scott (IPP-Garching)
  ■ Some experimental data already supplied to B. Scott (by PPPL)
  ■ Initial simulations started
• Add new lower-divertor view for more information about filaments (PPPL/MIT)
  ■ H-mode trigger near x-point? Poloidal extent of filaments?
• Radial view for structure parallel to B (PPPL/MIT)
• Purchase additional fast camera (PPPL), probably continuously recording (Phantom 7 or Photron APS-RX)
• Expand informal collaboration with Lodestar (Myra/D’Ippolito) to formal (i.e. PPPL $) for continued work on blob dynamics and density limit physics.
• Implement wide angle view with with fast camera
Near SOL: Critical gradient model appears to be consistent with edge characteristics

- Analytic & 3D transport models identify 2 dimensionless parameters controlling edge transport:
  \[ \alpha_{\text{MHD}} \sim q^2 R \frac{\nabla P}{B^2} ; \quad \alpha_d \sim \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right) \left( \frac{R}{L} \right)^{1/4} \]

- Electro-Magnetic Fluid Drift Turbulence (EMFDT) drives the behavior in models.

- Data suggest that near SOL plasma “self-organizes” toward a critical gradient, dependent on \( \nu^* \):
  - At fixed collisionality (\( \nu^* \) or \( \alpha_D \)), \( \nabla P \propto I_p^2 \) keeping \( \alpha_{\text{MHD}} \) constant.
  - H-mode data follows similar trends but higher gradients (\( \alpha_{\text{MHD}} \)).
  - Pedestal \( \nabla P \) also shows similar \( I_p^2 \) dependencies - pedestal talk.
Magnetic topology also appears to affect attainable pressure gradients

\[ \left| \nabla_{\perp} n_T \right| \]

\[ 10^{24} \text{ eV} \text{ m}^{-4} \]

\[ \frac{1}{q} \left( \frac{\lambda_{ei}}{R} \right)^{1/2} \sim \alpha_d \left( \frac{L_n}{R} \right)^{1/4} \]

\[ \alpha_{MHD} \]

- Lower-null achieves higher gradients ($\alpha_{MHD}$) compared to upper-null
- We believe this difference is due to changes in flows in the SOL - another control parameter
- Plans:
  - Extend ($\alpha_{MHD}$, $\alpha_D$) studies to higher $B$
  - New flow and ionization source diagnostics

Note - ($\lambda_{ei}/R)^{0.5}/q$ is a better fit than $\alpha_D$
Measurements from multiple machines point to a large poloidal flow in the SOL

• Flow along \( B \) towards the inner divertor
  ■ Peaked at the inner midplane
  ■ Likely related to D/C co-deposition at inner divertor
  ■ Dependent on magnetic topology & \( B \) direction

• Difficult for codes to reproduce
  ■ ExB drifts & Pfirsch-Schluter effects reproduce \( B \) dependence but not magnitude or poloidal variation
  ■ Experimental and modelling evidence for strong radial transport @ outboard edge driving parallel flows through pressure balance

• Also evidence of transport-driven flows setting toroidal rotation boundary condition for confined plasma

• Plans: additional flow measurements in the SOL (probes) and pedestal (CXRS).
Flows defined by magnetic AND/OR mechanical geometry - divertor or limited, again connecting to H-mode threshold

• Lower-limited, grazing, lower X-point equilibria have co-current inner SOL flows (not USN or inner-wall limited!)
  - Lower inner divertor recycling in common
  - Each have a low H-mode threshold
  - Flows towards the inner divertor are the consistent characteristic

• Plans:
  - New inner wall probes
  - New probe heads (poloidal and toroidal Mach flows)
  - CXRS (inner and outer edge)
UEDGE modeling of SOL flows is yielding insights into potential drive mechanisms

(A collaboration with A. Pigarov & S. Krasheninnikov, UCSD)

• C-Mod high-field SOL, near-sonic parallel flows, can be reproduced in UEDGE if cross-field transport coefficients have strong poloidal asymmetry\(^1\)

• Cross-field transport at the LFS midplane is predominantly convective; \(V_{\text{conv}}\) (sep) = 6m/s; \(V_{\text{conv}}\) (wall) = 160m/s

LFS/HFS radial transport asymmetry factor of 20:1

Plans (2006-2007)

• UEDGE to be enhanced to handle near DN equilibria (Rognlien - LLNL)

• Model upper/lower x-point and near double-null discharges

• \(\Rightarrow\) determine LFS/HFS transport asymmetry from C-Mod data

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\(^1\) A. Pigarov et al., presented at 10th International Workshop on Plasma Edge Theory in Fusion Devices
Inner-wall scanning probe diagnostic will allow detailed investigations of inner SOL plasma flows/profiles

- Two new inner wall scanning probes (WASPs) are to be installed in 2006 (grad student - N. Smick)
  - Probe actuated by embedded coil and ambient magnetic field
  - 4 electrodes $\Rightarrow$ Langmuir/Mach probe
  - Linear plunge motion (+R direction)

- Goals: Record key data in high field SOL (relatively free of ICRF sheath rectification effects):
  - Parallel & perpendicular flows
  - Fluctuations, fluctuation-induced transport
    - $\Rightarrow$ inward pinch?
    - $\Rightarrow$ quasi-coherent mode amplitude in EDA H-mode?
  - Density, temperature, potential profiles

- Prototype tested in 4T field last summer
- Final version to be tested prior to installation (next break)
Advanced, high-heat flux probes to be tested in 2006

- Goal: install on all 4 scanning probe systems
  - Parallel/perpendicular Mach probe geometry
  - Self-shadowing, tungsten electrodes

- Prototype fast sweep I-V probe drive electronics to be tested in 2006 (grad student - L. Lyons)
  - Graduate student thesis project
  - Proof of principle operation in 2006 on A-port probe
    - Voltage sweep rate $\sim$ 1 MHz
    - Record $T_e$, $n_e$, $\Phi$ fluctuations

- New Langmuir probe array in upper divertor
  - Installed as part of upper divertor/cryopump upgrade
Boronization was a central focus of the 2005 experimental campaign

- At the end of the 2004 campaign
  - The majority of Mo tiles were covered with thick B layers (~6 µm thick)
    - (note: such thick, widespread, layers are also common in carbon PFC tokamaks)
  - All surfaces cleaned of accumulated boron during vacuum break
    - Surface analysis showed B/(Mo+B) dropping from 99% to 10-20%
      - B likely ‘trapped’ in the topography of the surface
- All BN tiles replaced with molybdenum
- Long operational period before boronization to properly characterize un-boronized PFC operation.
Boronization is very important for plasma performance

- Molybdenum is the primary radiator before boronization (no B on walls)
- Fe and Mo fractions approaching 0.1%

- First boronization
  - Large drop in molybdenum & iron
  - Layer wears off in 10s of shots
- Second boronization
  - Molybdenum levels drop further

- Molybdenum radiation rises after each boronization - indications are that small regions (10-1000 cm²) are involved
- Iron radiation stays low after first boronization
  - Long-term coating of most surfaces
Boron coating erosion rate correlates with RF energy injected

• General trend seen after each boronization
  - Radiation low and stored energy high for a period
  - Followed by impurity increases and confinement degradation
  - Confinement degradation occurs at ~ 50 MJ input energy (for RF-heating)
• For Ohmic H-modes the degradation appears not to occur as quickly
  - ~3-4 times as much input energy to achieve the same degradation
  - => enhancement of sheaths in edge may be leading to enhanced erosion and Mo source
There is a clear correlation between higher impurity radiation and degraded confinement

- Mo radiation losses lead to a cooler pedestal
- Profile stiffness causes $T_e$ and $P_e$ to decrease across the entire profile
  - Lower stored energy and H-factor
- Reducing Mo (replaced w/B) leads to hotter pedestal and higher H-factor
  - Molybdenum radiation efficiency in C-Mod like W radiation in ITER
Boronization has a short-term effect on recycling and D retention

After an overnight boronization
- Amount injected to achieve the desired density very small
- Walls are fueling (R > 1)
- Gas seems to be coming from PFC surfaces near the midplane

- The recycling effects are mostly worn off after 50 shots
  - PFC surfaces shift from dominant fueling to almost pumping
- Long after boronization PFC surfaces pump
Boronization coatings (gain or loss) lead to dramatic effects in a high-Z tokamak

• Comparison of boronization on carbon and molybdenum PFC tokamaks shows similarities and differences

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<tr>
<th></th>
<th>Carbon PFCs</th>
<th>Molybdenum PFCs</th>
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<tbody>
<tr>
<td>Boronization effect</td>
<td>Lowers O, Fe, Ni, C&lt;br&gt;Increases B&lt;br&gt;Lowers recycling coef. (R&lt;1)?</td>
<td>Lowers Fe, Mo (O already low)&lt;br&gt;Increases B&lt;br&gt;Increases recycling coef. (R&gt;1)</td>
</tr>
<tr>
<td>Impurity reduction</td>
<td>10s of shots for C&lt;br&gt;Longer for Fe, Ni</td>
<td>10s of shots for Mo - small areas&lt;br&gt;Longer for Fe</td>
</tr>
<tr>
<td>time scales</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect of the layer</td>
<td>Small - B replaced by C, radiation low &amp; outside the pedestal - energy confinement still high.</td>
<td>LARGE - B replaced by Mo, radiation increases strongly, energy confinement degrades</td>
</tr>
<tr>
<td>wearing off</td>
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• C-Mod experience raises concerns for ITER/reactor regarding tungsten usage
Between-discharge boronization: a tool for finding impurity sources & optimizing operation

- Initial development of between-discharge boronization
  - Maintain constant conditions
  - Determine the most important molybdenum source location

- Scanned the boronization discharge resonance across the chamber
  - Most effective in reducing radiation @R=70
  - Effect lasts ~1 discharge consistent w/overnight boronization (which lasts longer)

- More experiments planned
  - Better locate Mo sources
  - Optimize speed and effectiveness
  - locally apply boron layer where needed

10’ period ~ 1/30 of overnight boronization period

![Graph showing PRAD (kW) before H-mode vs. resonance center (cm)]
Other avenues being pursued to identify important Mo sources & improve plasma performance

• The preponderance of data point to Mo sources in localized regions (toroidally, poloidally) and not at the divertor strike points. Possibilities include
  - Leading edges on top surface of outer divertor
  - Outer limiters, ‘gusset’ tiles…

• Diagnostic improvements being considered for next vacuum break
  - More spectroscopic views of the suspected surfaces
  - Cameras filtered for Mo I (source rate measurement covering most areas of chamber)
  - Quartz-Microbalance (determine the boronization deposition profile and erosion rate)
  - Coat suspected tiles with different elements as markers that will show up in plasma

• Experiments during the coming 10 week campaign
  - Continued inter-shot boronization development
    - More detailed studies of optimal deposition location
    - Enhance speed of process to minimize impact on shot cycle
  - During-shot boronization will be tried
  - Compare Mo I source magnitudes with different antennae, powers and locations.
Retention of injected gas larger than expected

• Tungsten is projected for use in a reactor due to
  - Nuclear damage in comparison to C
  - T retention in comparison to C (orders of magnitude lower)
  - BUT, further work is needed in the lab and tokamak to determine whether these advantages hold true.
• Molybdenum - very good proxy for W for H/D retention
• Initial C-Mod shot retention measurements of injected D₂
  - approaching 50%
  - Density threshold for high retention
  - Retention appears to decrease for constant shots
  - Dependent on strike point position & pulse length
• Further experiments needed
  - Understand saturation and density dependence
  - Identify location of pumping surfaces

Program Advisory Committee, January 25-27, 2006
Parallel effort to understand the process with laboratory experiments started

- Both at PISCES and U. Wisc. (DIONISOS) facilities
  - Samples from C-Mod irradiated with D plasmas (varying flux, fluence) and the D retention amount and depth distribution analyzed
- U.W. analysis of tiles from C-Mod for campaign-integrated D retention
  - D retention on plasma facing surfaces
  - D retention on tile sides
    - Can be substantial (~20% of overall D retention)
    - More difficult to remove (implications for ITER)
    - Some hints at deposition process

- C-Mod data in this area important for the ITER decision to proceed with high-Z first wall.

Plans - simulate C-Mod fluxes/fluence and temperature range with DIONISOS plasmas

Program Advisory Committee, January 25-27, 2006
C-Mod presents a unique opportunity to study hydrogenic retention (H/D/T) and high-Z material migration

- New diagnostic station being designed
  - Quartz-microbalance (next vacuum break)
    - Studies of deposition during boronization and plasmas
  - ARRIBA (Alpha Radioisotope Remote Ion Beam Analysis) - longer term
    - In-situ ion beam analysis of surfaces
    - Depth-resolved erosion/deposition, material mixing
    - H/D retention & recovery
  - Langmuir probes
    - Local characterization of plasma interacting with surfaces under study
Technique for removal of D/H retained in surfaces explored with initial success

**Idea** - concentrate heat flux locally to raise surface temperature - outgas H/D

- Disruptions release more gas than ‘regular’ shots or wall conditioning
- H removed through isotope exchange in the surface (HD as opposed to H₂)

- Gas recovered dependent on energy density as well
- Threshold increased over time
  - D stored deeper into surface

- More experiments planned
C-Mod divertor measurements central to benchmarking the ITER divertor prediction

• Two aspects of the ITER divertor modeling are being benchmarked against C-Mod data:
  ■ Lyman alpha trapping - potentially strongly affecting the ionization balance and access to detachment
  ■ Short neutral mean free path regimes - strongly affecting the neutral balance and pumping predictions

• C-Mod is ideally suited for this testing
  ■ Closest to ITER in both normalized and actual above physics parameters
  ■ Data available
  ■ Funding of interpretive modelling initiated 1 year ago (Lisgo, U. Toronto)
  ■ Part of IEA/ITPA DSOL-5 with JET
  ■ One of 5 US ITER physics tasks
  ■ First, low-density case results => several processes important
The newest modeled cases span a range of dimensionless and dimensional parameters

- Three cases now have initial models
  - Low density - $P_{\text{DIV}}=25$ mT (outer div. attached)
  - Med density - $P_{\text{DIV}}=75$ mT (outer div. detached)
  - High density - $P_{\text{DIV}}=150$ mT (x-point MARFE)
- The neutral densities span the ITER range =>
  - $\text{D}_2-\text{D}_2$ collisional mean free paths (1.3-7.8 mm), small compared to the divertor volume
  - $\text{D}^+-\text{D}_2$ collisional mean free paths also 1-8 mm, small compared to divertor fan
  - Photon absorption mean free paths ~ 1 mm
- Each < relevant dimension => excellent test of codes

Next steps
- Finish interpretive modelling
- Move on to self-consistent predictive modelling
Dust studies initiated

• Dust is studied for a number of reasons
  ■ Safety problems
  ■ Plasma impurities (plasma performance)

• Initial work concentrated on diagnostics
  ■ Dust characterization during vacuum breaks in collaboration with INEL
  ■ Dust quantity and dynamics during shots
    - Image analysis
    - MIE scattering

• Plans
  ■ Continued development of the above
  ■ Try to ascertain the origin of dust & how it affects the core plasma
Experiments in 2005 have resulted in an improved (and novel) upper cryopump concept

**Goal:** pumping for core and edge studies that separates heat and particle handling functions

- Experiments showed that the previous concept would have a high sensitivity to secondary strike-point location (~x3 variation in pressure)
- New ‘pumping slot’ concept
  - Less sensitive to strike-point location
  - Proximity to upper null also improves heat-flux handling
- Status/Plans
  - Tiles and support hardware manufactured
  - Cryopump fabrication & testing in next 3 months; Installation in summer 2006
**Tungsten tile development program underway**

**Goal:** ITER relevant tungsten tile development and operational experience

**Status**

- 12 tungsten rod tiles installed in C-Mod
  - No measurable W content in core
  - Tiles surviving at leading edges
- Design change from rods to lamellae (plates)
  - Simpler, cheaper - currently ITER aim
  - 1st tests at Sandia
    - Mechanical attachment failure
  - Design revised and new tests at Julich
    - TZM bolt holds lamellae together
    - Tests successful for a range of heat loads
- Material bought and design being finalized for a toroidal ring of tiles next break
C-Mod research well-aligned to ITPA high-priority research areas

The C-Mod boundary physics program addresses a number of high priority ITPA issues including:

• *Improve understanding of tritium retention & the processes that determine it.*
  - Understanding D levels on tiles and tile sides for B and Mo
  - Understanding removal of D at low tile temperature

• *Improve understanding of SOL plasma interaction with the main chamber.*
  - Wall flux measurements (‘main chamber recycling’)
  - Impurity influx and screening studies

• *Develop improved prescription of SOL perpendicular transport coefficients and boundary conditions for input to BPX modelling.*
  - Radial flux analysis - transport coefficients
  - Gradient scaling work (near SOL) connection to fluid turbulence theories
  - Dimensionless comparisons scalings of SOL characteristics across tokamaks
  - SOL flows and effect on core
C-Mod is actively involved in coordinated experiments across tokamaks & in support of ITER

• Our divertor/edge scientists seek out collaborations with other tokamaks in order to test ideas or gain new information

• The collaborations are encouraged through the IEA/ITPA framework
  - DSOL-3 ‘Study of radial transport’, B. Lipschultz organizer
  - DSOL-5 ‘Role of Lyman absorption in the divertor’, J. Terry, contributor
  - DSOL-4 ‘Comparison of disruption energy balance and heat flux profile’, D. Whyte, J. Terry, contributor
  - DSOL-11 ‘Disruption mitigation experiments’, D. Whyte organizer, R. Granetz, contributor
  - DSOL-13 ‘Deuterium co-deposition with C in gaps of plasma facing components B. Lipschultz, D. Whyte participants
  - DSOL-15 ‘Inter-machine comparison of blob characteristics’ J. Terry organizer

• The ITER team has requested that the US (C-Mod) advance the understanding of divertor radiation absorption through benchmarking codes - ITER-US subtask 3
Boundary Physics: Summary

• Our intent is to continue to make fundamental contributions with emphasis on the following:

  ✓ Steady state profile transport analysis to understand
    - Role of gradients in determining near SOL transport
    - Poloidal variations, machine scalings (to ITER), role of neutrals
  ✓ Edge flows importance in affecting impurities and the core plasma
  ✓ Turbulence studies
    - Turbulence relationship to large convective transport
    - Improved images/analyses/scalings/simulations & predictive capability
  ✓ Continued H/D retention and removal studies
  ✓ Develop separable divertor particle and heat control functions
  ✓ Optimize high-Z first-wall and divertor for long-pulse & high heat flux operation
    - Understanding boronization and its erosion
    - Development of strategies to extend the boronization layer lifetime