TRANSPORT PROGRAM

C-MOD 5 YEAR REVIEW

MAY, 2003

PRESENTED BY MARTIN GREENWALD

MIT – PLASMA SCIENCE & FUSION CENTER
Prediction and control are the ultimate goals of transport studies
- Experiments and theory have progressed to the point where meaningful, quantitative tests are being made.
- Theory/experiment comparisons drive the experimental program

C-Mod operates in unique regime in several important respects – crucial for validation of physics models

Facility Upgrades - important tools for transport research: shaping, heating, current drive (LHCD), particle control (cryopump).

Diagnostics – the tokamak is a scientific instrument
- Investment in high resolution diagnostics enabled edge studies.
- Lower Hybrid/AT/ITB program will increase emphasis on core plasma
- New (and upgraded) profile and fluctuation diagnostics are planned (DNB diagnostics, Thomson, PCI, Reflectometer, Scattering, etc)
• C-Mod program is imbedded in a national and international transport program

• We do not propose to answer, by ourselves, all important transport questions discussed in the plan

• We do propose to make substantial contributions in each of them however

• C-Mod will continue the close collaboration with theory and modeling groups.

• Our overall goal is theory and codes capable of meaningful prediction.

• Must go beyond “benchmarking” ⇒ co-development
  - Experiments guide extension of theory
  - Theory plays critical role in design of experiments
  - Comparisons need to include profiles, fluctuations and fluctuation dynamics
  ⇒ need to develop synthetic diagnostics
RELATION TO IPPA GOALS

The C-Mod Transport Plan directly addresses the following questions from the IPPA document section 3.1.1 and Appendix III:

- What determines the amplitude and width of the edge pedestals in plasma pressure and temperature?
- How does neutral hydrogen recycling affect stability and transport?
- What is the influence of the plasma edge on the plasma core and on the global properties of confined plasma?
- What are the effects of finite-β and confinement geometry on transport?
- What are the mechanisms responsible for anomalous electron thermal transport?
- How does the power threshold for internal transport barriers scale with gyroradius in the absence of externally driven rotation?
- What is the fundamental origin of the observed density limit on tokamak operation?
RECENT TRANSPORT HIGHLIGHTS

- Observation of rotation and momentum transport in source-free plasmas
- EDA H-mode – good energy confinement, with no impurity accumulation and no large ELMs
  - Tied to Quasi-Coherent mode – comparisons with simulations made
- ITBs with RF heating (no momentum or particle sources) created, characterized and controlled – models tested against GK codes
- Detailed comparisons between measured temperature profiles and non-linear gyro-kinetic calculations illustrate the role of electron dynamics in setting the critical gradient.
- L-H threshold characterized by local parameters and compared to first principles theory
- Dimensionless scaling of pedestal profiles – role of plasma vs atomic physics
- Role of turbulent transport in tokamak density limit investigated
C-MOD OPERATION IS UNIQUE IN SEVERAL IMPORTANT RESPECTS

• Compact, high field, high density
• Unique collisionality regime – high performance at high collisionality
  - $\nu^* \approx 0.1$ (but $\tau_{ei} \ll \tau_E$ thus $T_i \sim T_e$ in almost all regimes - reactor-like)
  - $\beta, \rho^*$ close to other performance extension devices
• RF heating and current drive – decouples source terms
  - No core particle sources, No momentum source
  - Heating decoupled from density profile
  - With ICRF, heating can be well localized and varied
  - With LHCD, no Ware pinch, no internal particle source
• C-Mod parameters lead to temperature gradients near critical gradient
  - Turbulence in regime close to marginal stability
• Provides an important platform for tests of transport theory
• Marginal Stability and Turbulence
  - Conduct tests of turbulent transport predictions near the marginal stability point.
  - Non-linear saturation mechanisms near critical gradients

• Momentum Transport – Without Direct Input Sources
  - Understand mechanism behind observed toroidal rotation
  - Importance of flows for regulating transport
  - ⇒ importance of self-generated flows

• Particle Transport
  - Investigate the origin and nature of particle transport – turbulent pinch
  - Importance of density profile for micro-stability
  - Lack of understanding of tokamak fueling mechanisms
OVERARCHING GOALS IN TRANSPORT TOPICS (CONT)

- **Electron Transport**
  - Assess the role of short wavelength fluctuations in driving electron energy transport
  - Can’t be neglected in the strongly coupled ($\tau_{ei} << \tau_E$) regime
  - No mechanisms have been ruled out so far

- **Transport Barriers**
  - Understand threshold or trigger conditions for bifurcation to internal and edge barriers
  - Access, dynamics, and control

- **Edge Pedestal: Height, Width, Relaxation**
  - Develop understanding and predictive capability for H-mode pedestal profiles
  - Critical boundary condition for core transport
MARGINAL STABILITY AND TURBULENCE

Issues:

- Theory predicts that transport should be near marginal stability.
- Gradients near critical values.
- Predicting temperature profiles ⇒ calculate non-linear stability.
- Can we verify this model?
- Can we verify the predicted non-linear saturation mechanisms for turbulence close to marginal stability?

Matching experimental profiles requires non-linear calculations and proper treatment of electron dynamics.

Matching experimental profiles requires non-linear calculations and proper treatment of electron dynamics.
(Turbulence near marginal stability) Plan:

- Quantitative comparison between non-linear calculations and experimental profiles, including $q(r)$, $V(r)$ measurements (MSE, CXRS, HIREX).
  - Verify the impact of magnetic shear, mean ExB flows
  - Correlation with ion-scale fluctuations (PCI, reflectometry).
  - Explore the origin and role of zonal or GAM flows in turbulence saturation, particularly the role of collisional vs collisionless damping of these flows.

- Exploit transient response to perturbations to investigate transport near marginal stability point.

- Look for evidence of transport events/avalanches, subcritical gradients or other evidence of SOC.
MOMENTUM TRANSPORT

Issues:

• Strong toroidal rotation in Ohmic and ICRF plasmas observed.

• ICRF specific mechanisms (Chang, Perkins, etc.) aren’t sufficient explanations.

• Origin of this self-generated flow?

• What are principal damping mechanisms for toroidal rotation? (momentum confinement)
Rotation and Momentum Transport - Plan:

- Continue testing of theories based on ion-loss/transport.
- Characterize momentum transport with transient transport experiments – including RF flow drive
- Look for consistency with turbulence based (Reynold's stress) explanations – fluctuation measurements.
- **Note**: much theory remains to be done here.

Profile evolution shows apparent transport of momentum from edge to core
PARTICLE TRANSPORT

Issues:

• Generally believed that particle transport is driven by ion-scale fluctuations

• Detailed calculations and measurements are lacking.

• Can we establish the connection between ion-thermal and particle transport?

• Turbulence driven pinch?

• Impurity and particle transport in EDA H-mode??

• What is the mechanism by which the QC mode alters impurity/particle transport?
(Particle Transport) Plan:

- Transient transport experiments – including impurity injection
- Comparison with emerging theoretical models for particle transport.
- Compare with thermodiffusion and turbulence equipartition models
  \[
  \frac{\nabla n}{n} \propto \frac{\nabla T}{T} \text{ or } \frac{\nabla q}{q}
  \]
- Pinch? With $E_\phi = 0$?
- Continue investigation of profile and transport changes across ELMfree/EDA boundary.
- Correlation with fluctuations (PCI, BES, reflectometry), particularly high frequency modes predicted by BOUT code.
ELECTRON TRANSPORT

Issues:

- Ion modes can't explain all transport phenomenology
  - Regimes with $\chi_e$ anomalous but $\chi_i, D \sim$ classical
  - Global transport scaling: ion dominated vs electron dominated regimes (L-mode vs neoAlcator).

- Are short wavelength (electron-gyroscale) important?

- Can we identify the mechanism and underlying drives for electron-scale turbulence?

- Is there a role for magnetic fluctuation driven transport $\langle \tilde{B} \tilde{T}_e \rangle$?
(Electron transport) Plan:

- Look for short wavelength (electron-scale) fluctuations, compare with theoretical predictions (PCI, scattering)
  - Enhanced PCI system should allow spatially resolved measurements of $k_r$, $k_\theta$ in appropriate range (2D?)
- Look for $T_e$ fluctuations (HECE)
- Study equilibrium and transient transport in low collisionality (decoupled) regimes (cryopump for density control).
- Investigate role of short wavelength magnetic fluctuations in driving edge transport (fast scanning probe with $B_p$ loops)
TRANSPORT BARRIERS (CORE)

Issues:

• Stabilization of ion-scale turbulence in fully developed ITBs is fairly well understood.

• Much less known about the access conditions or triggers for ITB.

• Can we use the heat pulse as a sensitive probe in the barrier?

• Can we understand and control the location of the barrier through changes in heating profile or through control of the current profile?

• Can we understand the relative contributions/effects of ion and electron heat transport in various ITB scenarios?

• Can we trigger barriers directly through RF flow drive?
(Transport Barriers) Plan:

- Detailed experimental and theoretical studies of micro-stability just before formation of the barrier (gs2).
  
  o Include effects of heat deposition, flow shear, current profile, density profile.

- Investigate role of current profile, heat deposition, etc. in determining location of barrier.

- Heat pulse propagation studies with intrinsic (sawteeth) and external drive (MC heating). – relation to marginal stability paradigm.

- Test RF flow drive scenarios (MCIBW, MCICW)
  
  o Powerful tool – if it works
TRANSPORT BARRIERS (L/H THRESHOLDS AND TRANSITION DYNAMICS)

Issues:

- Despite many years of study, there is still no widely accepted theory for L/H transition/threshold.
- Features like the $\nabla B$ drift effect are unaccounted for.
- Can we understand the basic dynamics and identify the critical parameters of the transition?
- Are interactions between the edge and SOL plasmas, particularly flows, important for the transition?
(L/H transitions and threshold) Plan:

- Detailed measurements of **local** parameters and profiles at transition.
  - Identify critical variables/thresholds.
  - Compare with emerging models
  - Investigate edge turbulence and transport in L-mode.

- Exploit new capabilities for shaping (including double null), heating.

- Attempt to stimulate transition directly through $E_r$ modification by generation and loss of fast ions at edge with local heating.

- Characterize bifurcation and transition dynamics
Additional Issues:

- Can we establish the dominant physics/scaling for pedestal width?
- Plans will stress local measurements and physics
  - What is the relative role of plasma vs atomic physics? Is there a role for the SOL plasma?
  - Is the "characteristic length scale" approach correct?
  - If so what is/are the important scales? (R, ρ, L_s, L_n0,...)
  - If not, what is the role of heat and particle flux?
Additional Issues:

- Pedestal pressure gradient is approximately given by ideal MHD stability,
- Mechanisms which enforce the gradient vary dramatically (ELMS I, II, III, EDA, etc.).
- Can we understand which mechanisms operate in which regimes?
- Map out regimes in local and global variables for L-mode, ELMfree H-mode EDA, type I, II, III ELMs
  - Create phase diagram for regimes
  - Vary heating power, density, plasma shape, and plasma current.
  - Control pressure gradient, collisionality, magnetic shear
- Compare results in detail with theories for micro- and macro-stability.
<table>
<thead>
<tr>
<th>Date</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Marginal Stability &amp; Core Turbulence</strong></td>
<td>Role of magnetic shear, ExB shear</td>
<td>Transient experiments – incl. Avalanches, SOC</td>
<td></td>
<td></td>
<td>Origin and role of zonal/GAM flows</td>
<td></td>
</tr>
<tr>
<td><strong>Momentum Transport</strong></td>
<td>Fast ion loss mechanisms</td>
<td>Transient momentum transport experiments</td>
<td>Test Reynold’s stress models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Particles</strong></td>
<td>Particle transport modified by QC fluctuations (EDA)</td>
<td></td>
<td></td>
<td>Correlation with ion thermal transport</td>
<td>Correlation with fluctuations</td>
<td></td>
</tr>
<tr>
<td><strong>Electrons</strong></td>
<td>Role of magnetic fluctuations - Edge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Short wavelength fluctuations</td>
</tr>
<tr>
<td><strong>Transport Barriers Core &amp; Edge</strong></td>
<td>L/H Threshold – studies of local quantities</td>
<td>ITB Trigger Detailed comparisons with non-linear stability codes – Role of shear, ExB, η</td>
<td>Transients, Heat Pulse Propagation Studies, bifurcation dynamics</td>
<td>Predict &amp; control strength, location of barrier</td>
<td>Test RF Flow Drive Scenarios</td>
<td>Exploit if successful</td>
</tr>
<tr>
<td><strong>Pedestal Width, Height, Relaxation</strong></td>
<td>H-Mode Regime “Phase Space” Characterization</td>
<td>Plasma vs Atomic Physics – Pedestal Width</td>
<td>Pedestal Physics and Scaling – role of shear, collisionality</td>
<td></td>
<td></td>
<td>Detailed comparisons with micro- and macro-stability</td>
</tr>
</tbody>
</table>
GOALS FOR TRANSPORT PROGRAM

• Conduct comprehensive tests of turbulent transport predictions for C-Mod near marginal stability point.

• Understand mechanism behind observations of core toroidal rotation and transport of momentum

• Evaluate the relation between particle and energy transport
  o Verify the existence and importance of anomalous pinch
  o Determine the origin of increased particle transport in EDA H-modes

• Assess the role of short wavelength fluctuations in driving electron energy transport.
  o Evaluate the importance of magnetic transport in plasma edge

• Understand the threshold or trigger conditions for bifurcation to internal or edge transport barriers

• Develop understanding a predictive capability for H-mode pedestal profiles
• The C-Mod experiment offers excellent opportunities to advance the state of transport science
  - Capable and unique facility
  - Strong diagnostic set
  - Wide collaborations with theory and modeling

• All three of these components will be improved and expanded over the next five year period.

• Expect transport program to be dominated by close and careful comparisons with theory
  - Though still plenty of room for new discoveries.