OVERVIEW OF THE ALCATOR C-MOD PROGRAM

IAEA-FEC November, 2004
Alcator Team
Presented by Martin Greenwald
MIT – Plasma Science & Fusion Center
C-Mod is compact, high field, high density, high power density

- $B_T$ to 8 T, $I_P$ to 2 MA
- $P_{ICRH}$ to 6 MW

- Equilibrated ions, electrons
- No core momentum source
- No core particle source

SOL Turbulence and Transport

- Self Generated Flows and Momentum Transport in the Core and Edge
- H-mode Threshold
- Control of ITBs
- ICRF – Mode Conversion
- Locked Modes Disruptions
- LHCD and Other Near-Term Plans
Edge turbulence dominated by large structures

- Edge turbulence visualized with high-speed camera (250,000 fps).
- Large, field aligned structures, “blobs”, account for most turbulence and transport.
- Analysis shows these structures move poloidally inside separatrix and accelerate radially outside.
POLOIDAL ASYMMETRIES IN SOL PROFILES AND FLUCTUATIONS SUGGEST THAT HIGH-FIELD SIDE IS POPULATED VIA FLOWS FROM LOW-FIELD SIDE

- SN plasmas have the same pressure on both sides.
- Fluctuations are always much lower on the high-field side (ballooning).
- DN plasmas have very low pressure on the high-field side.
- The self-generated “symmetrizing” flows are observed (M ~ 1)
STRONG TOROIDAL ROTATION IN ABSENCE OF EXTERNAL TORQUE
IS THERE A CONNECTION TO BOUNDARY PHYSICS?

TO REVIEW

- Strong self-generated toroidal flows
- Rotation increases in co-current direction as plasma pressure increases
- Decreases with $I_P$
- Mach numbers up to 0.2-0.3
- Similar trends seen for RF and OH heated plasmas – not an RF or fast particle effect

Rotation Increases with Pressure

![Graph showing rotation increases with pressure](image)

- $\Delta V$ (10^4 m/s)
- $\Delta W$ (kJ)

(Plasma Pressure, Power)
MOMENTUM IS TRANSPORTED INWARD FROM OUTER REGIONS

- Evolution of rotation profiles following transitions can be modeled to yield transport coefficients
  - EDA – diffusive
  - ELMfree – large inward convection as well
- Important role for boundary
- In all cases, transport is much faster than neo-classical
SELF-GENERATED CORE AND EDGE FLOWS EXTREMELY SENSITIVE TO MAGNETIC TOPOLOGY

- Scan separation between primary and secondary separatrix (SSEP)
  - SSEP < 0 Lower null
  - SSEP > 0 Upper null
- Over a few mm, rotation shifts in counter direction by 20-30 km/s
- Scale comparable to SOL size.
- Links core and edge rotation
- Double null balance is critical
Observations of self-generated flows and inward momentum transport lead to a novel hypothesis for $\nabla B$ drift influence on L-H threshold.

- Power/temperature threshold is 2x higher for unfavorable topology - $\nabla B$ ion drift away from SN.

- Edge rotation is sum of the two terms just described.
  - Topology dependent (from symmetrizing of ballooning transport) – more counter for unfavorable geometry.
  - Pressure (power) dependent – increases in co-current direction

- For unfavorable topology, discharge begins “farther” from threshold state.
CORRELATION BETWEEN TOPOLOGY, ROTATION AND THRESHOLD IS STRONG

- A few mm change in SSEP result in 0th order changes in rotation and threshold.
- Comparable in distance to SOL width!!
- SOL apparently provides crucial boundary condition for core rotation.
- Large variation for shots labeled “DN” by EFIT.

Rice-EX/6-4
**VB Effect is Only Part of the L-H Threshold Story**

- Simulations: suppression of drift-Alfven turbulence via zonal flows. *(Rogers 1998)*

- Guzdar *(PRL 2002)* derives analytic formula.

\[
\Theta \equiv \frac{T_e}{L_n^{1/2}} = 0.45 \frac{B_T^{2/3} Z_{\text{eff}}^{1/3}}{(R A_i)^{1/6}}
\]

- Splits difference between favorable and unfavorable topologies.

**L-H Threshold Compared to Analytic Theory**
• Barriers formed in C-Mod with off-axis ICRF heating.

• Steep density profiles, with $\chi_{\text{EFF}}$ reduced to ion neoclassical levels across entire core.

• Application of on-axis power arrests density peaking and allows control of particle transport (impurity accumulation).

• Barrier foot position is not linked to RF resonance location (or whether resonance is on low or high-field side).
Barrier foot location depends mainly on $B_T$.

- Barrier position can be varied from $r/a \sim 0.3-0.6$.
- Strongest scaling is with $B_T$.
- Weaker scaling seen with $I_p$.
- Barrier foot location at $q_\psi \sim 1.1 - 1.35$.
- Magnetic shear may be the critical parameter?

![Graph showing the relationship between $R_{\text{density foot}}$ (m) and $B_T$ (T) with data points at 70 MHz and 80 MHz. The graph indicates a trend line and data points within the range $765 \text{kA} < I_p < 800 \text{kA}$.](image-url)
• Off-axis heating flattens $T_e$, begins to stabilize ITG.

• With reduced diffusivity, Ware pinch causes density to peak.

• TEMs are destabilized by $\nabla n$.

• Discharge reaches steady state when TEM diffusivity balances Ware pinch.

• Barrier strength controlled by on-axis heating via $T^{3/2}$ dependence of turbulent diffusivity.
FLUCTUATIONS SEEN WITH PCI MAY SUPPORT ITB SCENARIO

- PCI has very high S/N, dynamic range, wide bandwidth (to 5 MHz)
- Fluctuations at $k\rho_s \sim 0.3 – 1.0$ increase as barrier develops
- TEM?
- Future work will help localize fluctuations and extend $k$ range.
• Power Deposition Measurements Validate Simulations of Mode Conversion Process

• Off-axis deposition with 23% H, 77% D (measured) at 80 MHz

• Ion-ion hybrid layer at \( r/a = 0.35 \)

• Total efficiency
  o Experiment 20%
  o TORIC 18%
ICRF MODE CONVERSION PROCESS STUDIED IN DETAIL WITH FLUCTUATION DIAGNOSTIC AND ADVANCED SIMULATION

- Parallel version of TORIC with \( n_r = 240, n_m = 255 \).
- Resolves details of MC process.
- D/He3 at 50 MHz
- All three waves - FW, IBW, ICW – seen in experiment with phase contrast imaging diagnostic (PCI).
Set of external non-axisymmetric control coils installed.

Allow determination of intrinsic error field and mode locking threshold.

Dimensionless identity experiments performed w/JET, DIII-D.

Weak size scaling found.

Locked modes should not be worse for ITER than for current machines.

Coils allowed suppression of locked modes, 2 MA operation.

C-Mod, DIII-D, JET data in same range for $n/n_{\text{limit}}$.

5x range in machine size.

Hutchinson EX/P5-6
SIGNIFICANT DROP IN HALO CURRENT MAGNITUDE AND ASYMMETRY WITH MODIFIED DIVERTOR GEOMETRY

- Previous work found that halo currents scaled with $I_p/q_{95}$ with strong poloidal asymmetry.
- After divertor modification, same scaling observed but with lower magnitude (1/2) and less asymmetry.
- Drop in halo current may be explained by change in plasma/divertor contact during VDE.
- *Nota bene* for future machines.
FUTURE WORK: EMPHASIZES AT RESEARCH AND SUPPORT FOR BURNING PLASMAS (ITER) IN REACTOR RELEVANT REGIMES

- Reactor relevant conditions
  - Ions and electrons coupled; $T_i \sim T_e$
  - $t_{\text{PULSE}} > \tau_{L/R}$
  - No core momentum or particle sources.
- Enabled by LHCD
  - 3 MW source at 4.6 GHz.
  - 4 x 24 waveguide array – realtime phase control
- Cryopump for density control
- Prototype tungsten brush divertor tiles to help manage heat load.
- Long pulse DNB.
The End