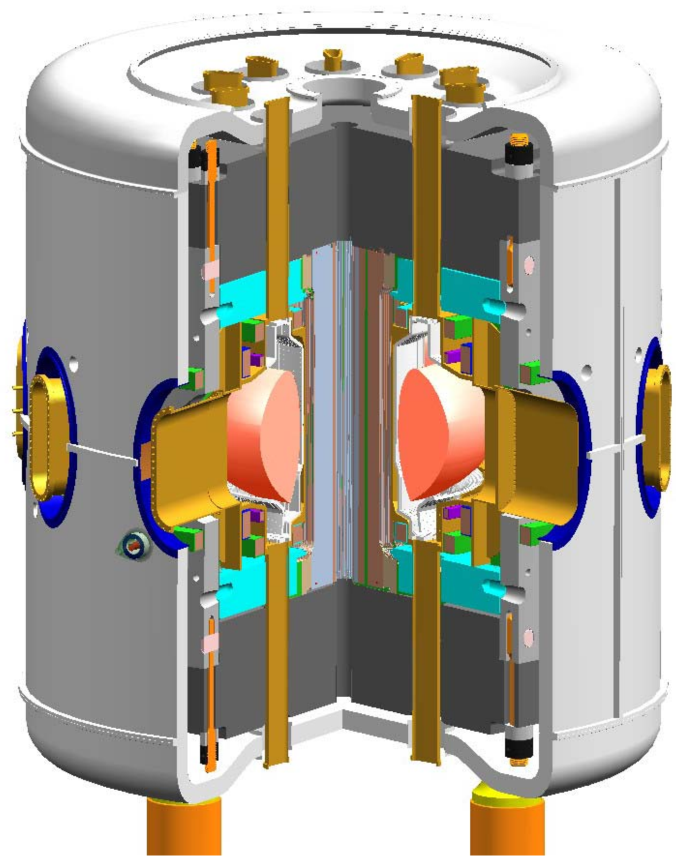
Alcator C-Mod: Research Highlights and Plans

Alcator
C-Mod



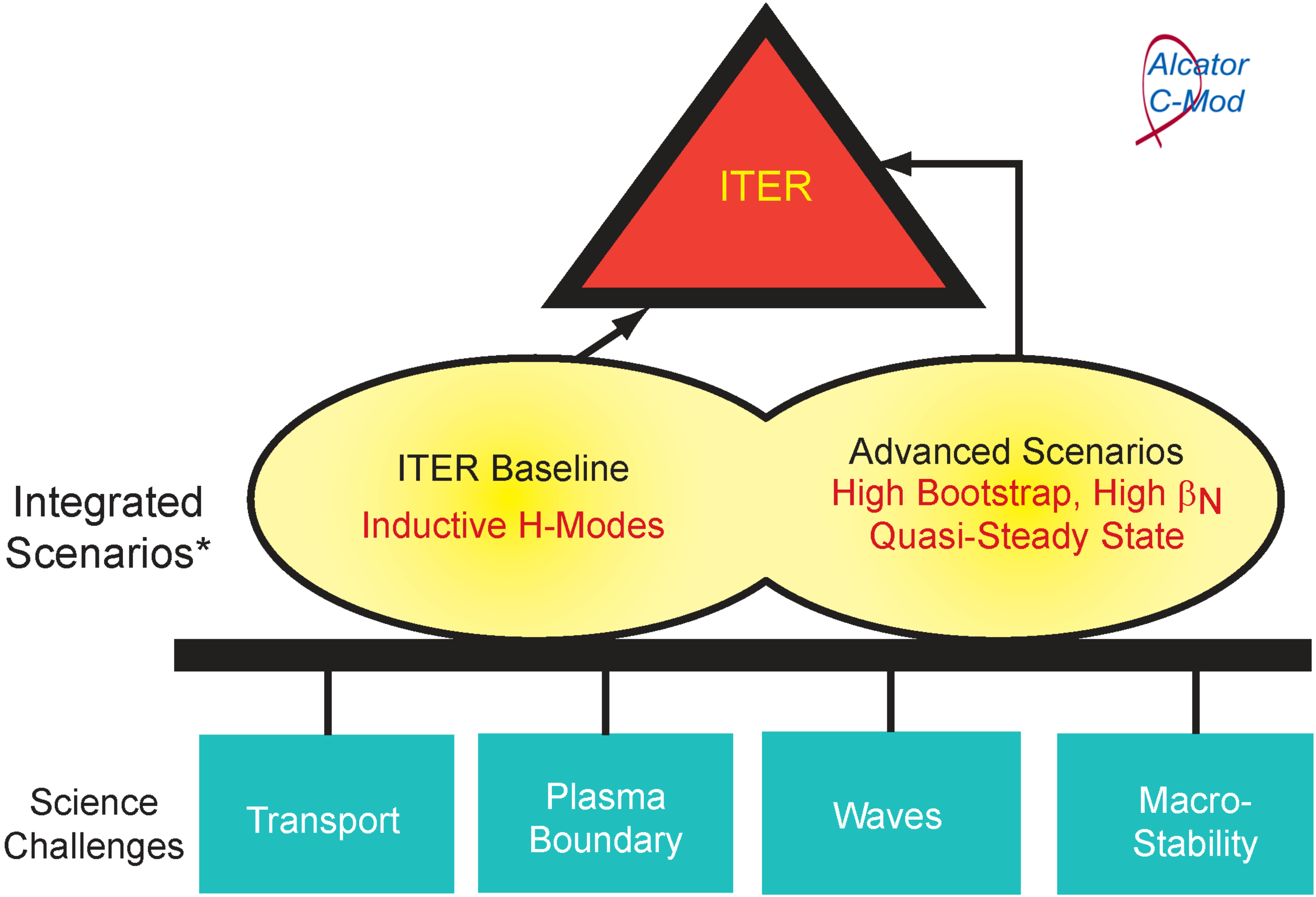
Fusion: Pathways to the Future

Fusion Power Associates Annual Meeting
and Symposium

September 27, 2006

Presented by E.S. Marmar

on behalf of the C-Mod Team

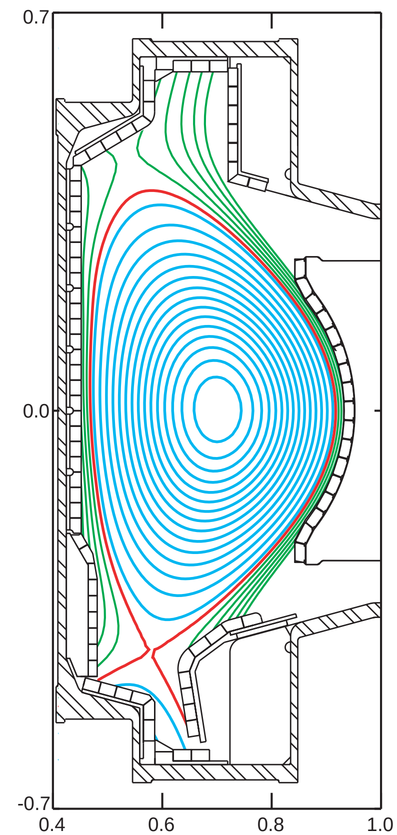


*Equilibrated electrons-ions, no core momentum/particle sources, RF I_p drive

C-Mod well positioned to help solve challenges for ITER

- Unique regimes
  - ITER B field, density, power density, plasma pressure
    - Disruption mitigation
    - Neutral opacity, Radiation Transport
  - High leverage database contributions
    - Dimensionally unique
    - Non-dimensional match to larger, lower field tokamaks
- ITER heating and current drive tools
  - Lower Hybrid Off-Axis CD
  - ICRF minority heating, MCCD
  - Torque and particle source free
    - Transport-driven rotation
- All-metal high-Z Plasma Facing Components
  - Molybdenum → Tungsten
    - Tritium retention, Impurity dynamics, Detachment
  - Low-Z wall coatings

C-Mod



B_T = 5.3T, I_p = 1.6MA

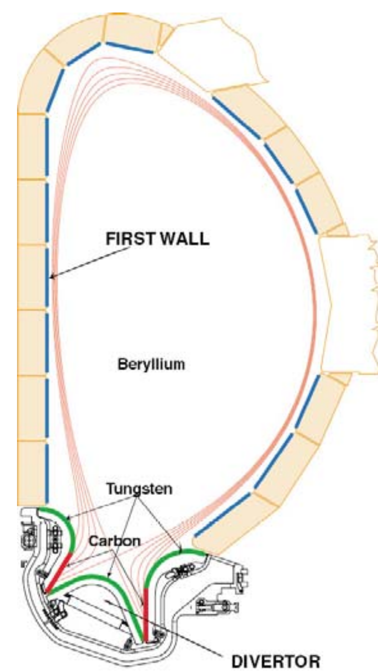
$B \leq 8.1$ T, $I \leq 2.0$ MA

$\beta_N \leq 1.8$, $Z_{eff} \sim 1.5$

$0.1 \times 10^{20} < n_e < 10 \times 10^{20}$

$P_{\parallel}(SOL) \leq 0.5$ GW/m^2

ITER/9



B_T = 5.3T, I_p = 15MA

$\beta_N = 1.75$, $Z_{eff} < 1.6$

$n_e = 1 \times 10^{20}$ m^{-3}

$P_{\parallel}(SOL) \approx 1$ GW/m^2

C-Mod plays a major role in education of the next generation of fusion scientists

Alcator C-Mod

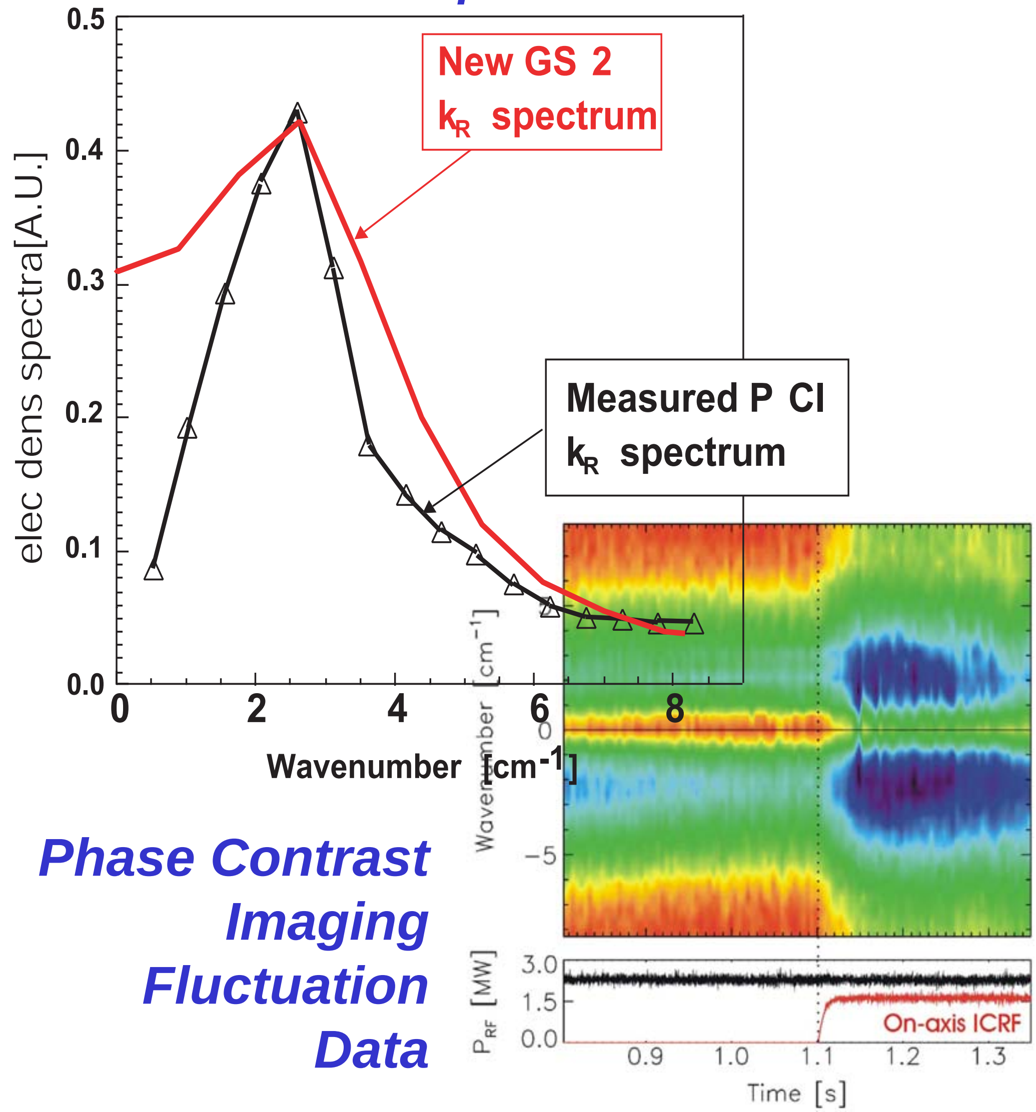
- Typically have ~25-30 graduate students doing full-time Ph.D. research on C-Mod
  - Nuclear Science & Engineering, Physics and EECS (MIT)
  - Collaborators also have students utilizing the facility (U. Texas, U.C. Davis, U. Wisc., Politecnico di Torino, U. Cologne/Germany, ASIPP/China)
  - Current total is 31
- MIT undergraduates participate through UROP program
- Host National Undergraduate Fusion Fellows during the summer

Detailed Comparisons of Experiment with Advanced Non-Linear Models Reveal Details of Transport

Alcator C-Mod

- Major dependences undergoing test
  - Collisionality
  - Magnetic shear
- Steady improvement in profile measurements
- Major upgrades to fluctuation diagnostics: PCI, Reflectometry, BES, HECE
- Synthetic diagnostics for gyrokinetic codes "constructed"

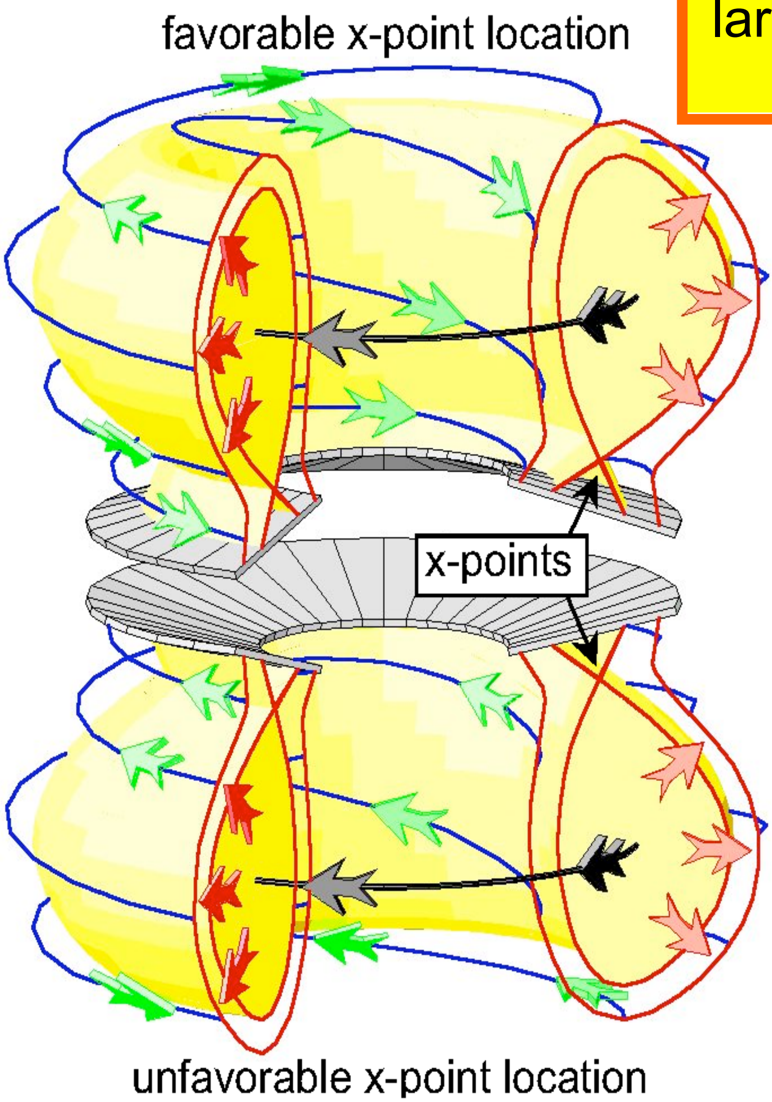
Comparison with Synthetic Spectra



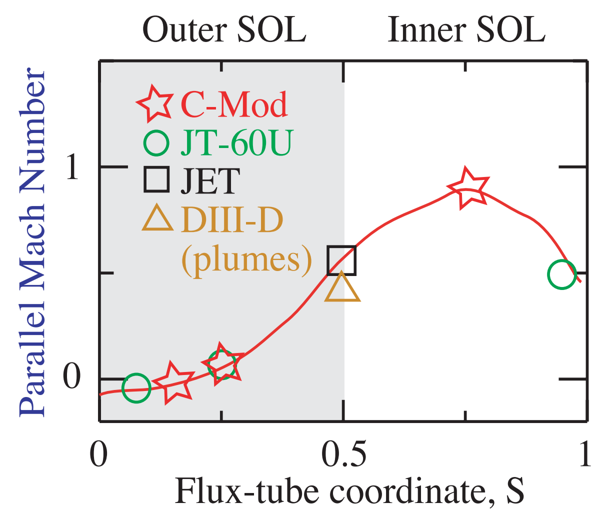
Phase Contrast Imaging Fluctuation Data

Strong Flows seen on Open Field Lines
Flow Direction Changes with Magnetic Topology

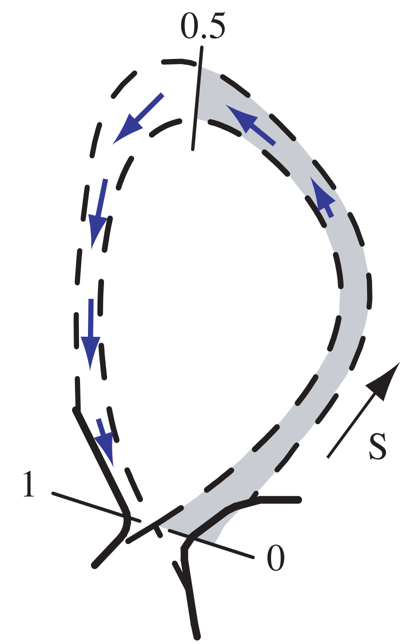
Alcator C-Mod



Cross-field transport (and turbulence) stronger on large R (low B) side of the torus (ballooning)



Toroidal component of Scrape-Off-Layer flow changes direction with magnetic topology



Flows on Closed (Core) and Open (SOL) Surfaces are Well Correlated

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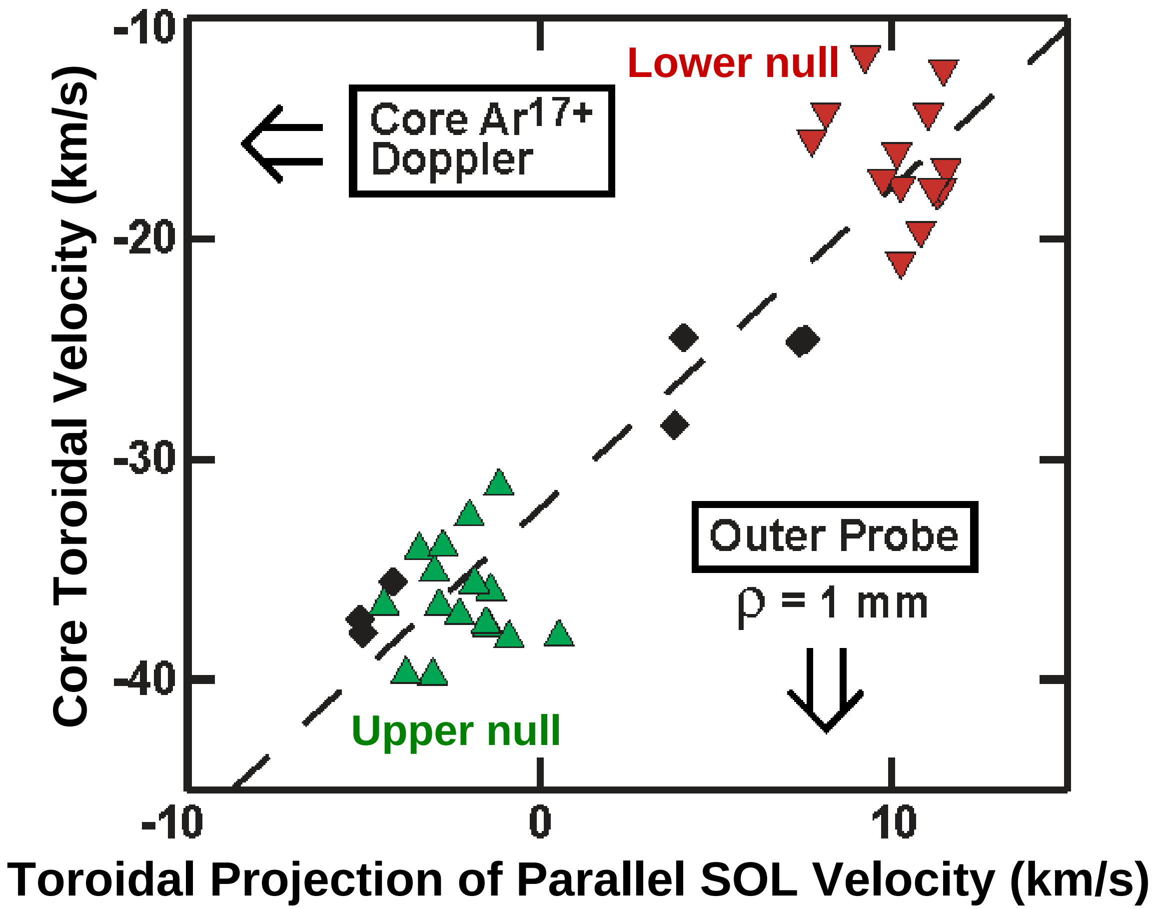

- Note: Core and Scrape-Off Layer flows track but are not identical
- Still need to investigate momentum transport through the edge confinement barrier

These Observations May Explain Topology Dependence of H-Mode Threshold

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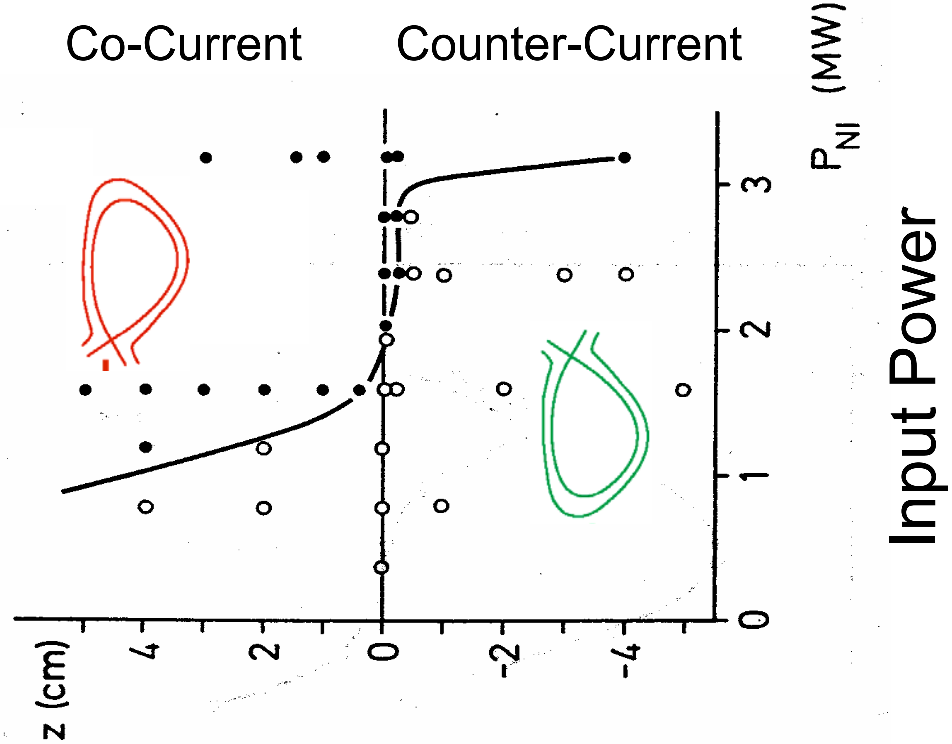
- The L/H Power threshold is typically ~2x higher when topology is reversed
- One of the long-standing mysteries of tokamak physics
  - First reported on ASDEX in 1989
- “Universal” result

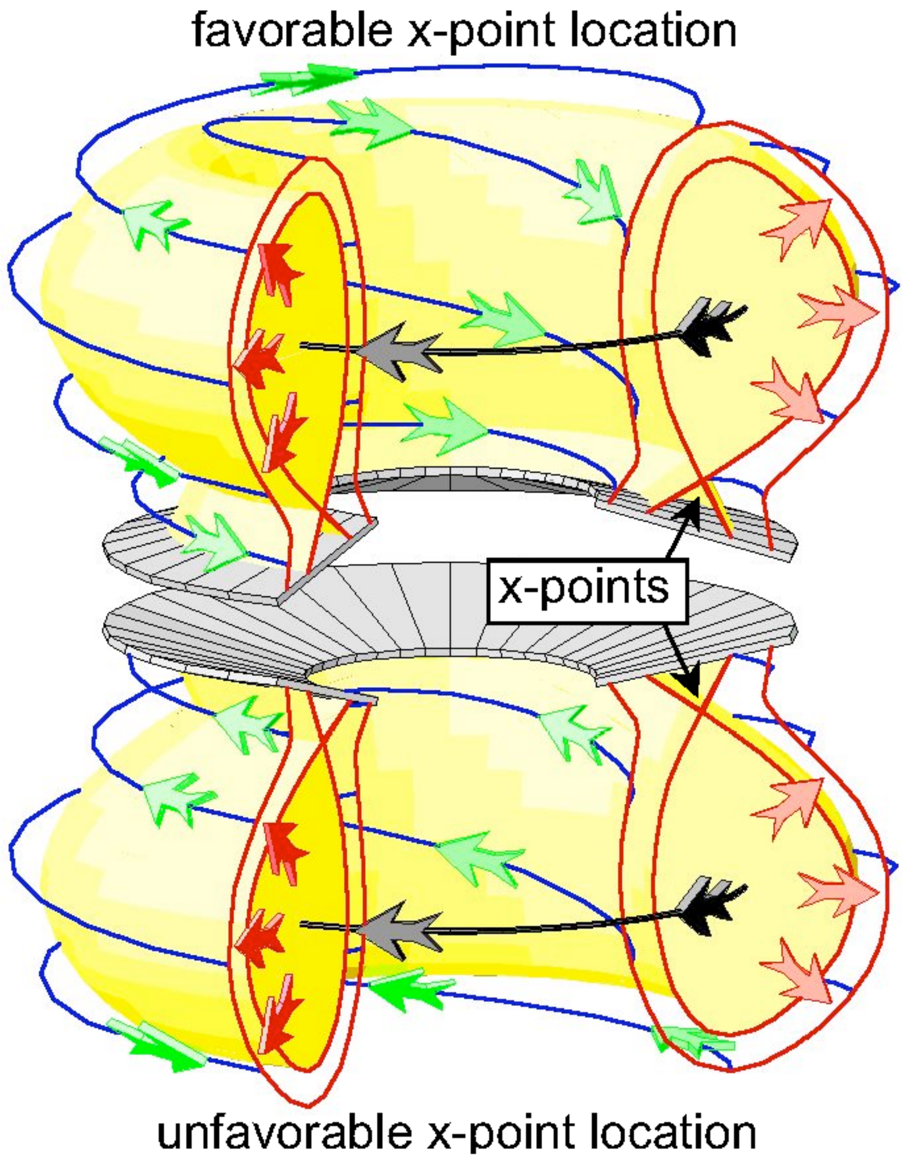
SOL Flows (Implied by C-Mod Results):



Asdex 1989

L-H Story In Words…

- Significant parallel flows are driven in the SOL as a result of poloidally asymmetric cross-field transport (ballooning).
- These flows reverse direction with respect to the plasma current depending on whether the x-point is at the top or bottom of the machine and couple to toroidal rotation in the confined plasma
- There is a separate effect in which both the SOL and core flows increment in the co-current direction when the plasma pressure (input power) is increased.
- So these two effects add or subtract depending on the topology → topology effect on threshold.
- ***How does momentum couple through the edge?***
- ***How does this work quantitatively with the details of flow-shear stabilization and such?***



Gas-Jet Disruption Mitigation Looks Promising At ITER-like Plasma Parameters

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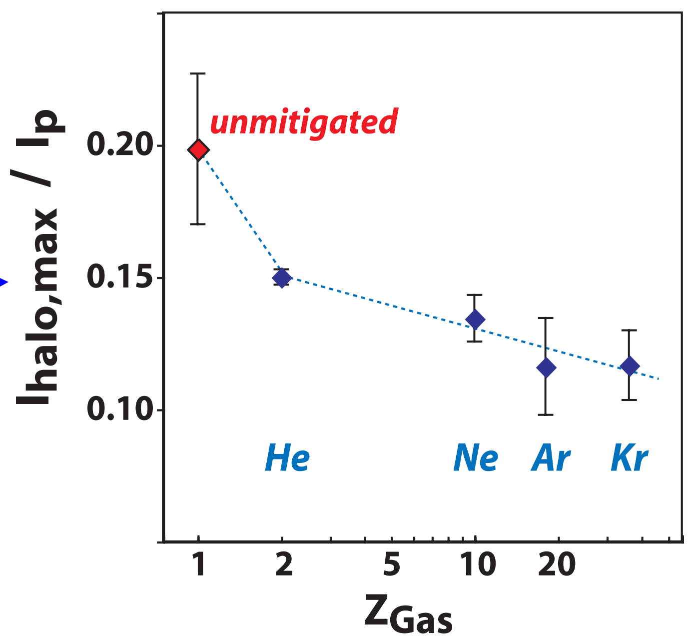
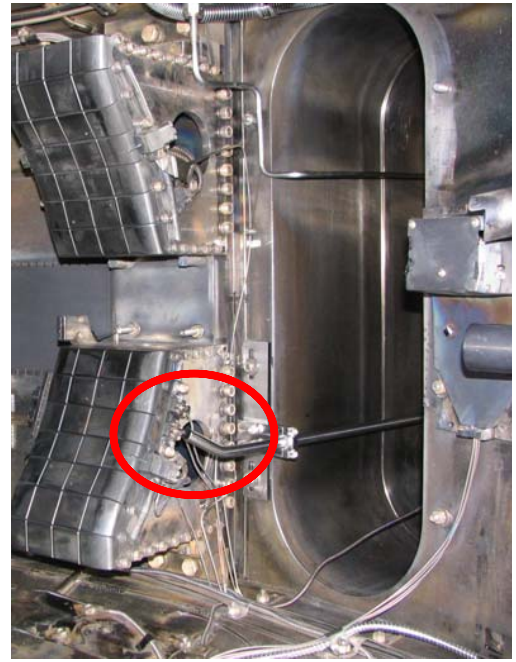
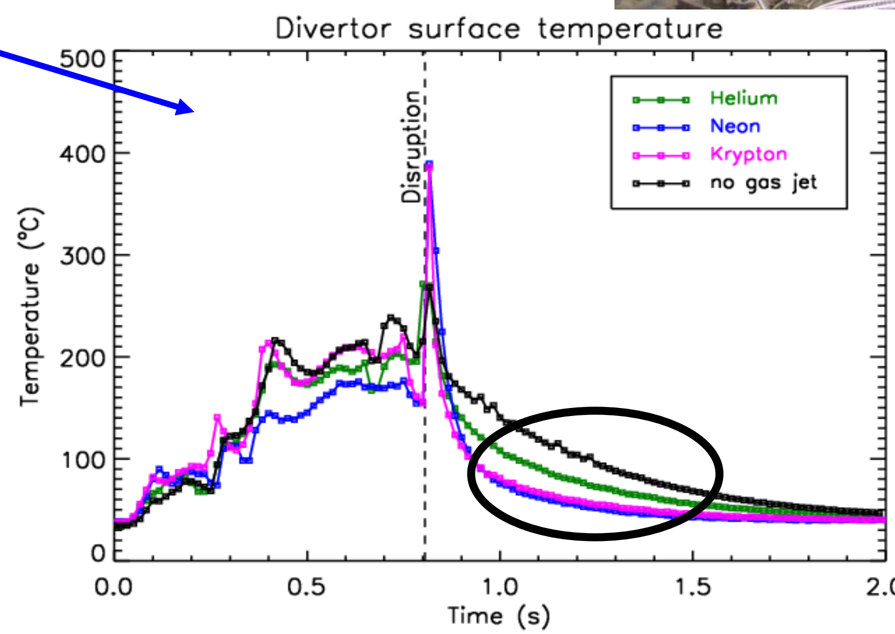
- Halo currents are reduced by as much at 50%
- Mitigation improves with Z of noble gas
- High fraction of plasma energy is converted to benign radiation
- Less heating of divertor surfaces
- No runaways observed
- No effect on following discharge
- Reliable, reproducible
- Digital plasma control system has been used to detect start of VDE in real time, fire the gas jet and mitigate disruption







Extended MHD (NIMROD) Simulations: Nonlinear Mode Interactions Plays A Major Role

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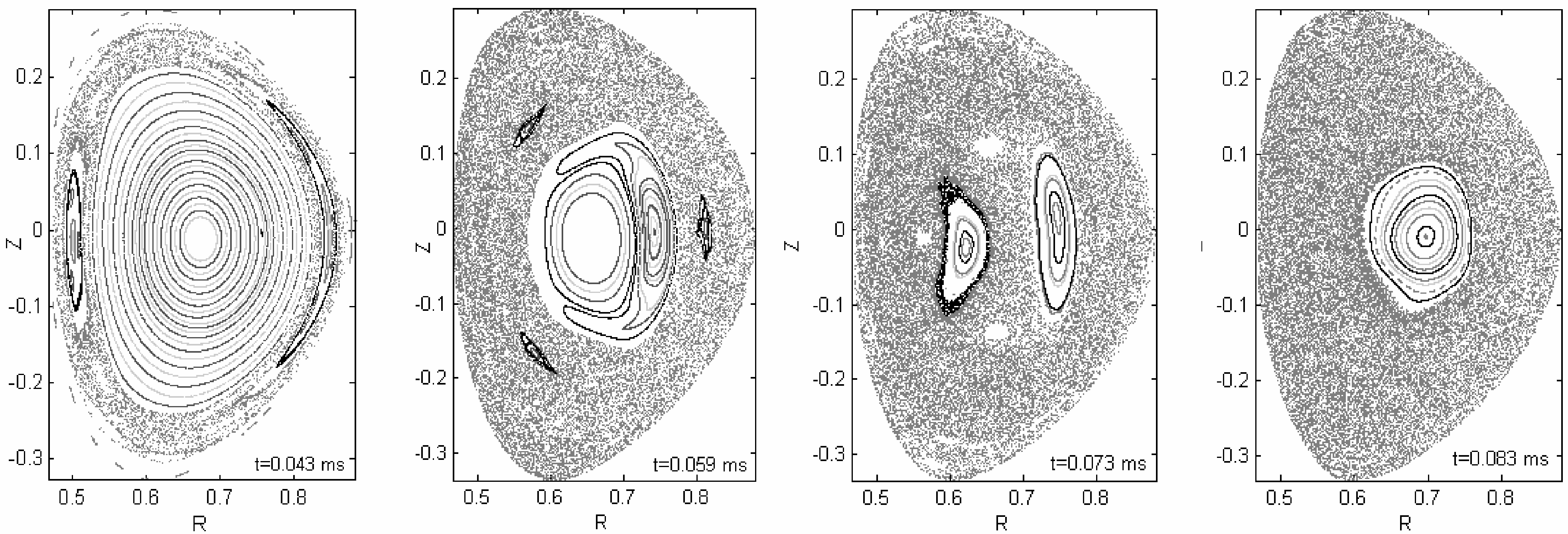
Fast cooling of edge region triggers rapid growth of MHD modes

2/1, 1/1 modes cause large ergodic region: core cools, impurities mix in



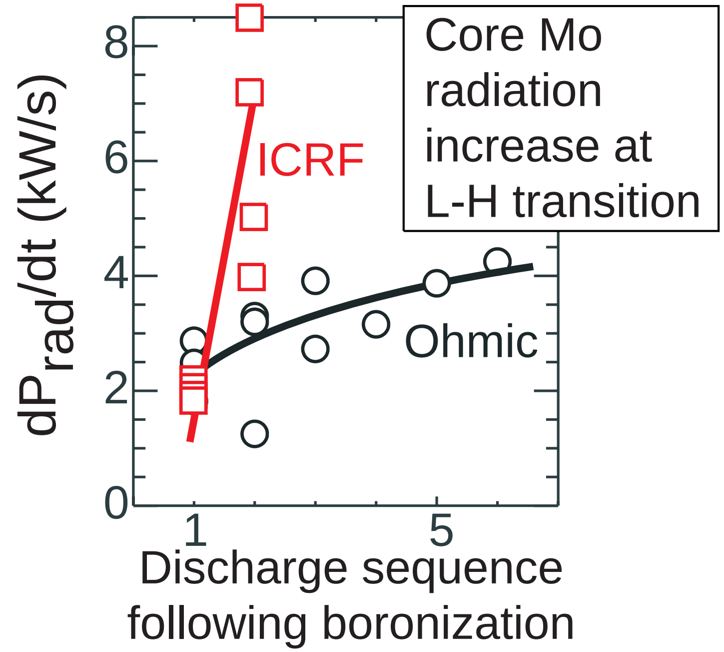
Deep gas jet penetration IS NOT NECESSARY

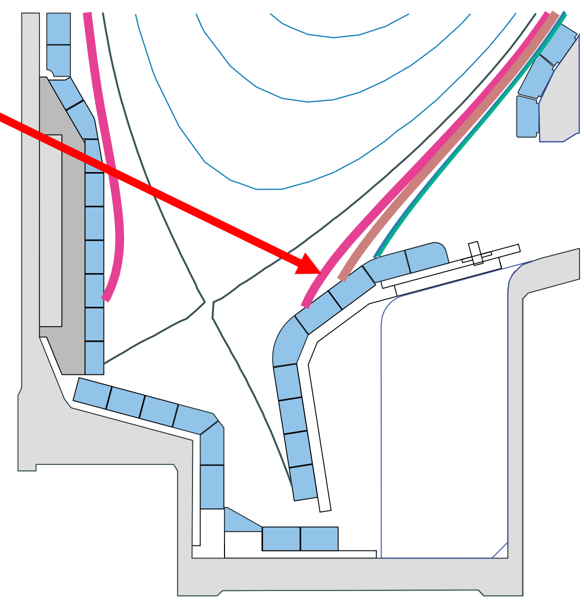
∴ ITER relevant

Wall Conditioning: Boron Erosion Linked to ICRF Sheath Rectification

Alcator C-Mod

- ICRF quickly erodes boron films
  - Mo uncovered, enters core plasma
- Local intra-shot boronization used to identify key location: top of the outer divertor
- Scrape-Off Layer field lines connect antennas to same location
  - Induced RF sheaths measured: 100-400 Volt
  - Use of alternate antennas confirms picture
- ITER tungsten divertor tiles in similar location





Lower Hybrid Current Drive

Key Advanced Tokamak Tool

Fully non-inductive 1 MA Plasma

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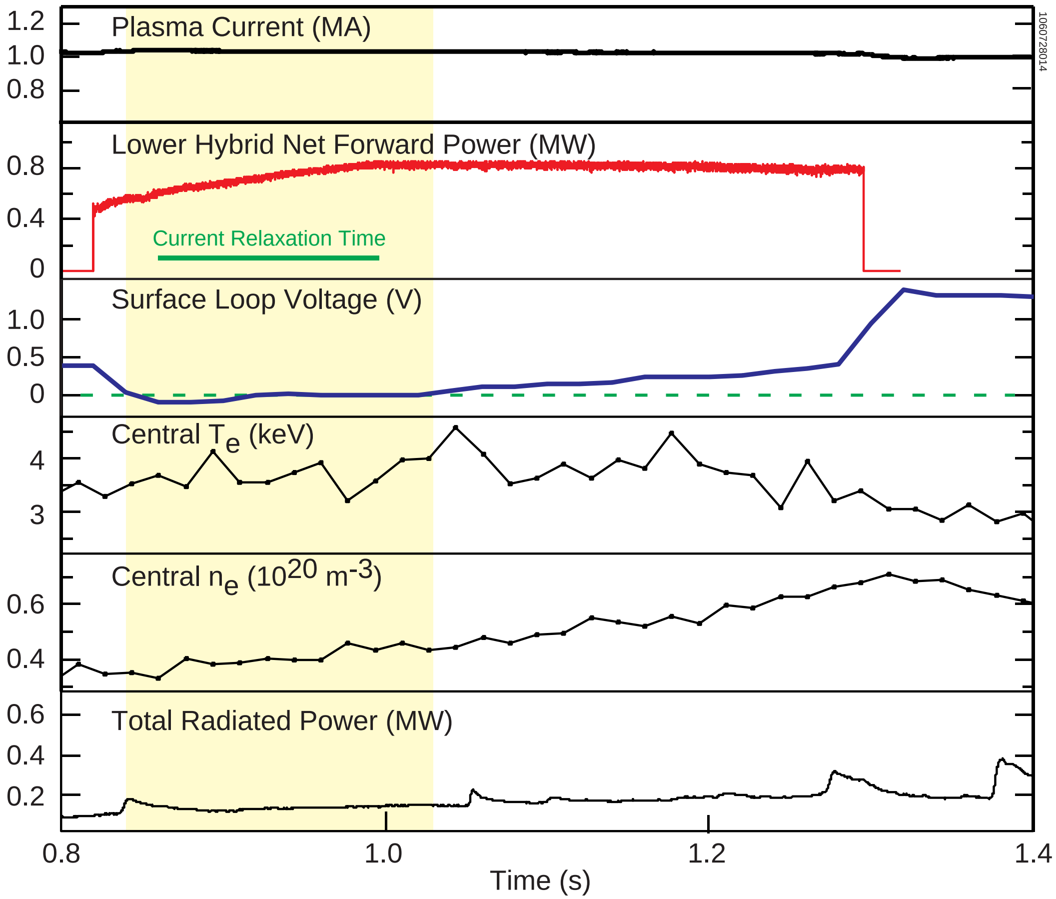
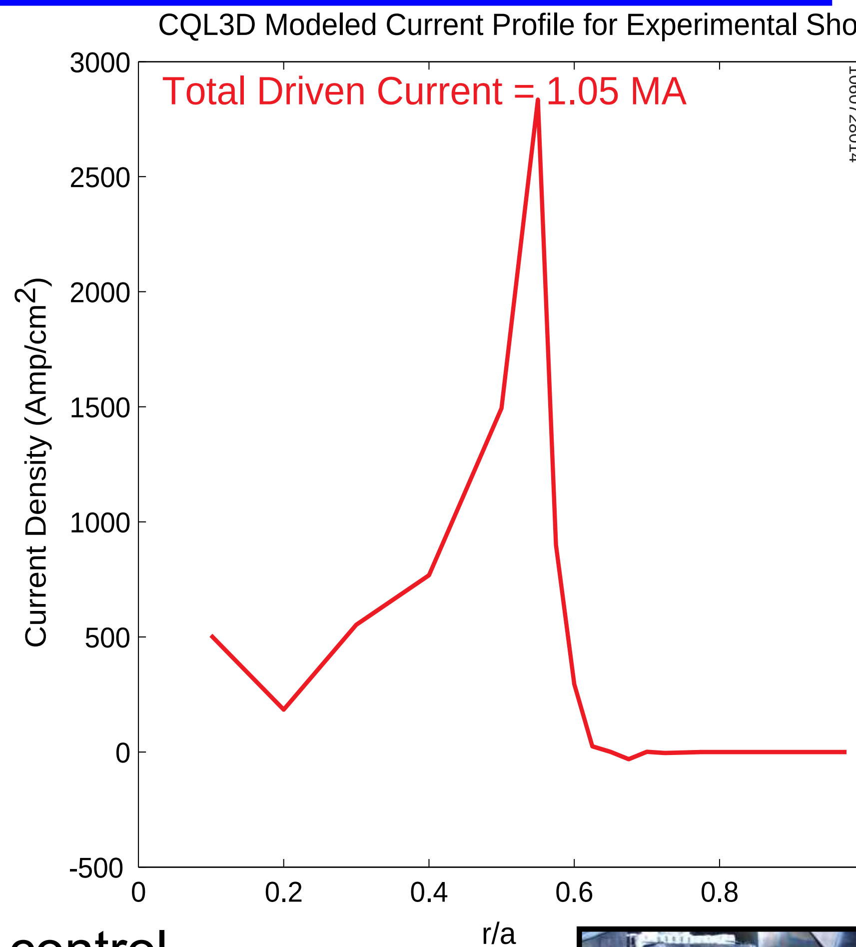
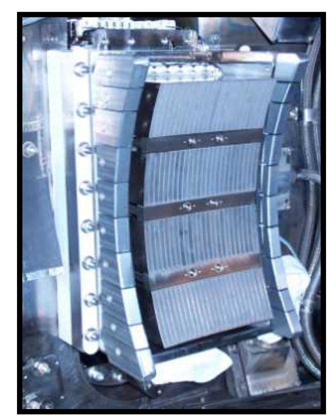




- RF off-axis current drive and current profile control
- Simulation predicts current driven off-axis (r/a~0.55)
  - Total driven current in excellent agreement
- Consistent with hard x-rays, sawtooth stabilization, reduced inductance
- Current drive efficiency is high $n_0IR/P \sim 0.4\times10^{20}$ A/(W•m^2)



C-Mod Unique in World and US
Among High Performance Divertor Tokamaks

Alcator C-Mod

Unique in the World:

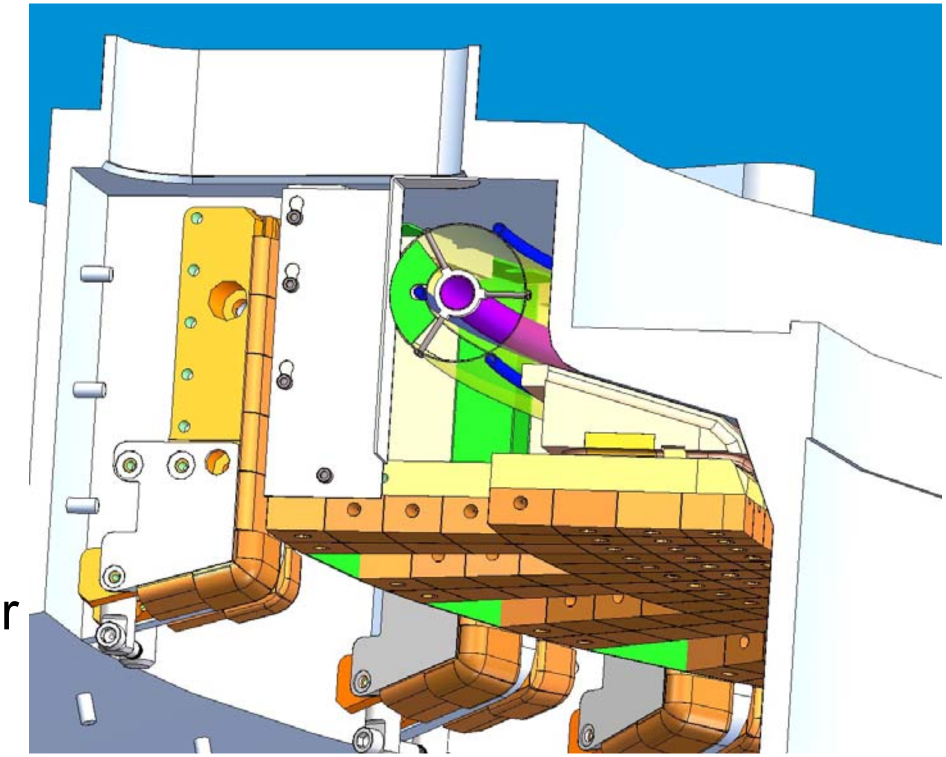
- Only high field, compact, high performance divertor tokamak
- All metal high-Z plasma facing components
- Highest pressure and energy density plasmas
- Particle and momentum source-free heating and current drive
- Equilibrated electron-ion coupling
- ITER level Scrape-Off-Layer Power Density
- Approach ITER neutral opacity, radiation trapping

Exclusive in the US :

- ICRF minority heating
- Lower Hybrid Current Drive
- Premier US Facility for Graduate Student training

Exciting Prospects for the next 2 years (and beyond)

- Cryopump for density and particle control
  - Lower collisionality H-Mode regimes
  - Efficient LH current drive
  - Isotope control
- New and Upgraded Diagnostics
  - Profiles, fluctuations
- Exploit combined Lower Hybrid and ICRF
  - Higher power H-Modes with j(r) control
  - Weak shear/hybrid inductive modes
  - Reverse shear/Internal Transport Barrier regimes
    - Leading to fully non-inductive (~10 skin times) up to the no-wall β limit
- Addressing key questions for ITER baseline operation
  - Confinement, Heating and Current Drive, High Z Plasma Facing Components, Disruption Mitigation
- Increased emphasis on AT regimes



Protection Hardware

84 support plates
840 TZM tiles