Status of Tokamak Research

Alcator
C-Mod

Alcator C-Mod and the Path to ITER and Beyond

Forum on the Future of Fusion

Fusion Power Associates Annual Meeting and Symposium

November 20, 2003

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on behalf of the C-Mod Team

We are technically ready to begin ITER construction

- Science and Technology issues to resolve, including
  - All metal plasma facing components: T retention, disruptions
  - Disruption Mitigation in high pressure plasma
  - Transport/Confinement with equilibrated electrons and ions
  - Pedestal physics: desire for small/no ELM regimes; scaling
  - NTM physics: direct stabilization; elimination of sawtooth seed
  - Rotation in the absence of direct momentum input: implications for RWM stabilization
  - Error fields and locked modes: size and field scaling
  - Alfven Eigenmode physics
  - AT physics toward steady state

C-Mod Demonstrates Compatability of all Metal (Mo) PFCs with Clean, High Performance Plasma

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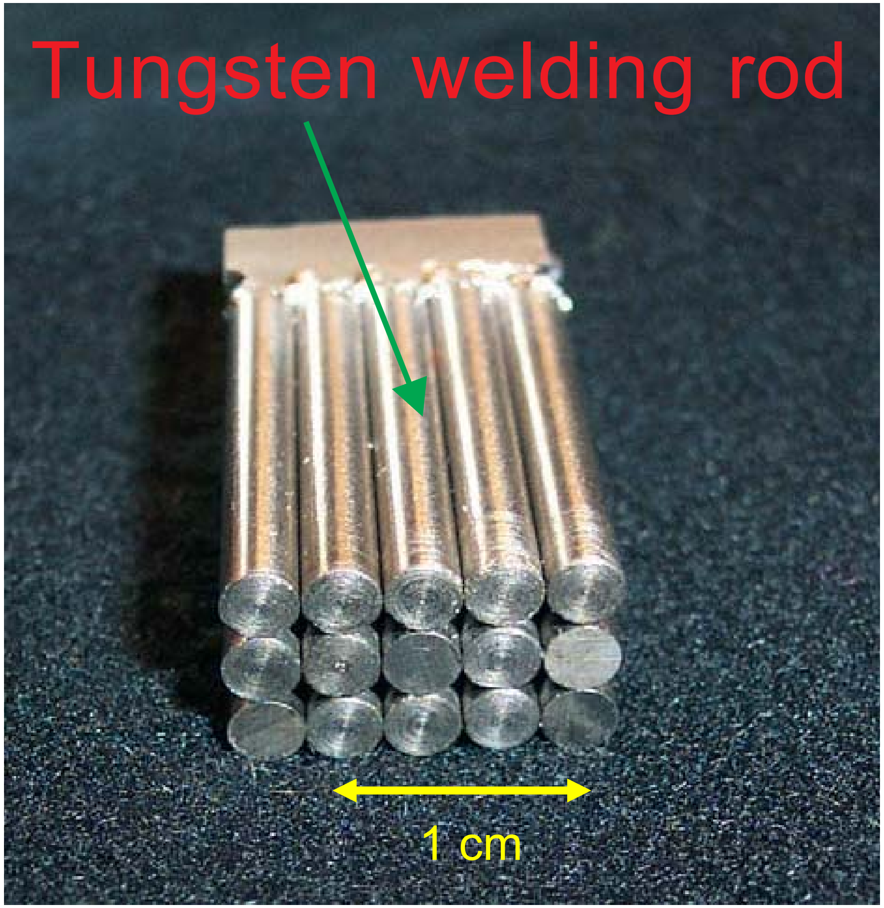
- Tritium retention may preclude carbon from ITER and Power Reactors
- C-Mod operates with reactor relevant edge power densities ($P_{||}$ up to 0.5×10^9 W/m^2)
  - Z_{eff} in range from 1.2 to 2 under most conditions
- Planning for even higher power at lower n_e (AT regimes)
  - Investigating ITER prototypical tungsten brush designs (collaboration with Sandia National Lab)
  - Install first modules in C-Mod, March 2004
- Disruptions can cause surface melting



Disruption Mitigation needs Testing in Higher Electron Pressure Plasmas

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- Massive noble gas puff on DIII-D
  - Very encouraging results (D. Whyte, et al., PRL 2002)
- C-Mod investigations (collaboration with U. Wisconsin):
  - Higher Electron Pressure (P_e) plasmas (gas penetration)
  - Higher Energy Density plasmas (efficacy of radiation)
- C-Mod/DIII-D/JET comparisons valuable to test size scaling

Device	$\langle P_e \rangle$ (kPa)	$P_{e,0}$ (kPa)	a (m)	$P_{gas\text{-}jet}$ (kPa)
DIII-D	~8	30	0.6	30
C-Mod	10-150	40-400	0.22	300
JET	~15	~60	0.92	
ITER	250	500	2	>200?
FIRE	900	1800	0.6	
IGNITOR	800	2500	0.47	

Small/No ELM Regimes Highly Desirable

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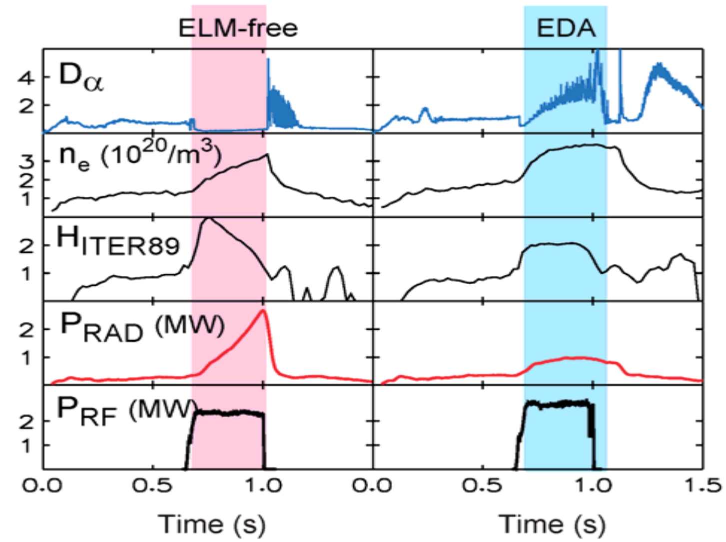
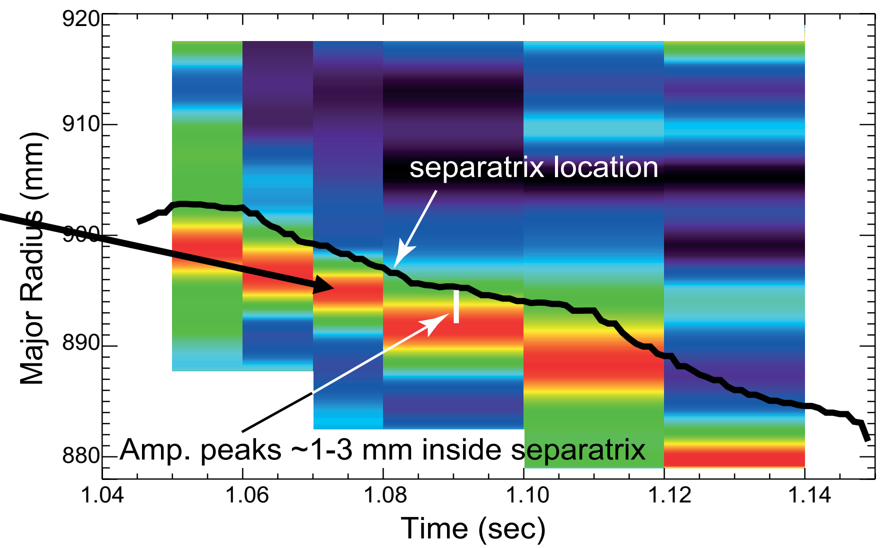
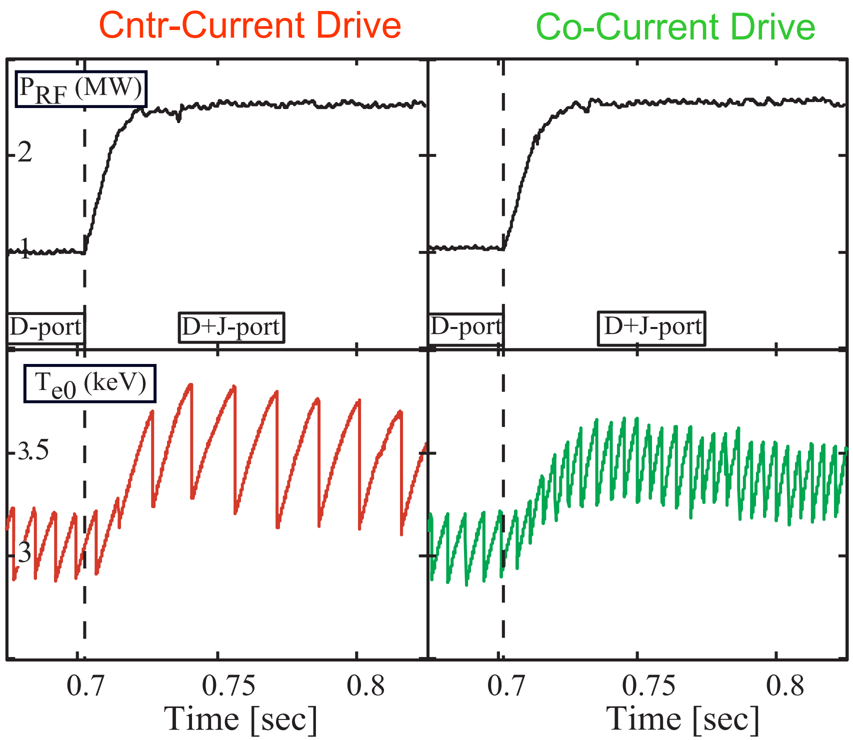
- Giant ELMs could compromise ITER divertor in small number of discharges
- Small/no ELM regimes with good energy confinement, particle regulation across barrier:
  - QH/QDB modes (DIII-D, also now on ASDEX-U, JET)
  - EDA H-Mode (C-Mod, also now seen on JFT2-M)
- Particle transport in EDA driven by mode just inside separatrix
  - Features consistent with resistive ballooning mode seen in modeling (Xu and Nevins)

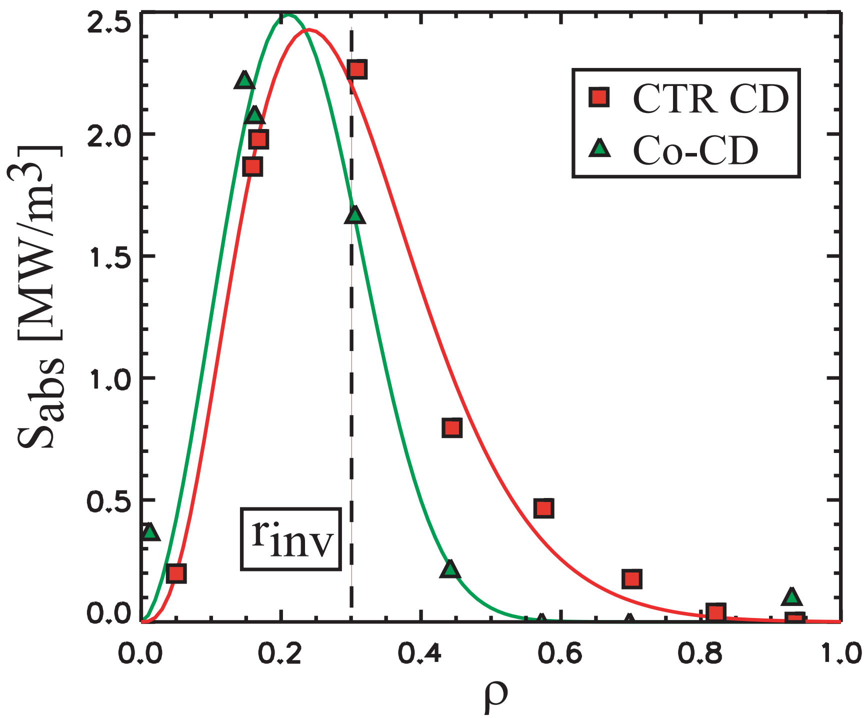
Enhanced D_α (EDA) H-Mode





Off-Axis ICRF MCCD Experiments
Potential for Sawtooth Stabilization with modest RF power





- Mode Conversion Current Drive: D(^{3}He), 8 Tesla
- Localized absorption on electrons (300 kW) just inside the sawtooth inversion radius
  – Counter-CD phase lengthens τ_{st}, Co-CD phase shortens τ_{st}
- More power available
  – Stabilize sawteeth? (remove seed for NTM)
  – Direct NTM stabilization?

Momentum Input Difficult in a Reactor Important to Understand Spontaneous Rotation

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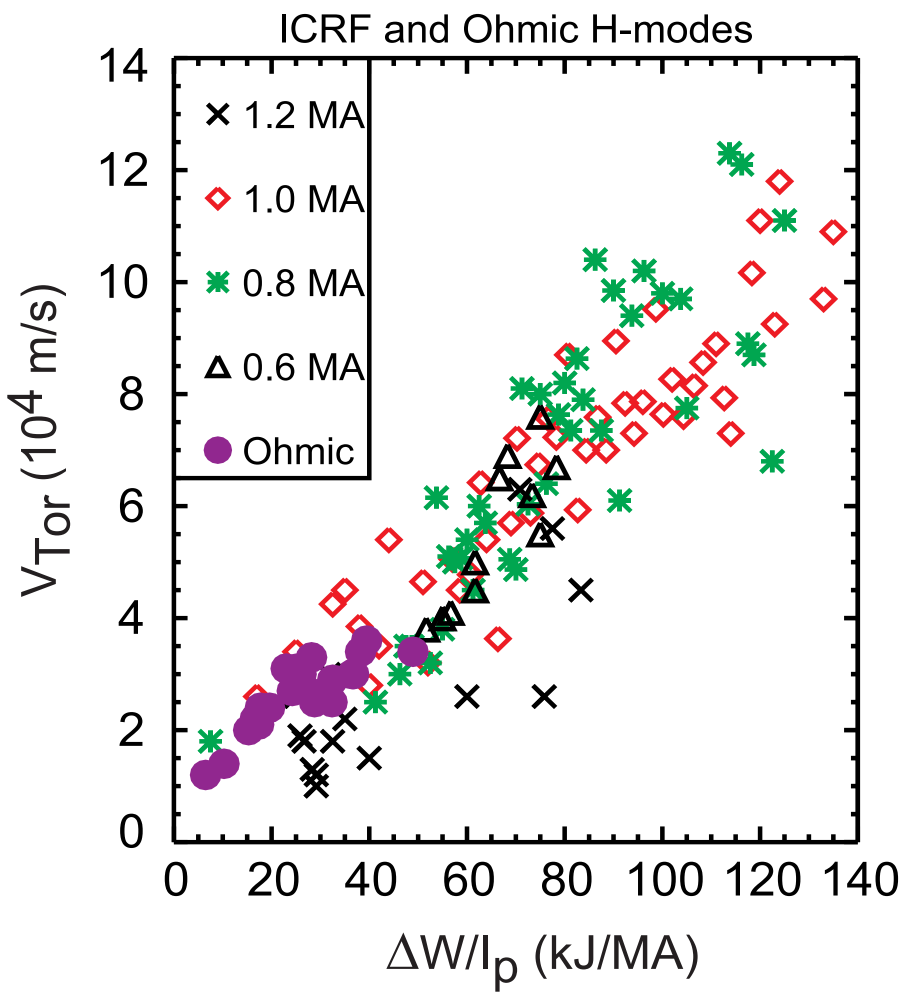
- Spontaneous rotation in high pressure (gradient?) plasmas
  - Appears to be a transport effect; not due to RF or fast ions
- Need to understand underlying mechanism
- Also seen on Tore-Supra and JET
  - Masked by beam torque in most other experiments
- Scaling to ITER?



Non-axisymmetric error fields can cause locked modes: loss of confinement; disruption

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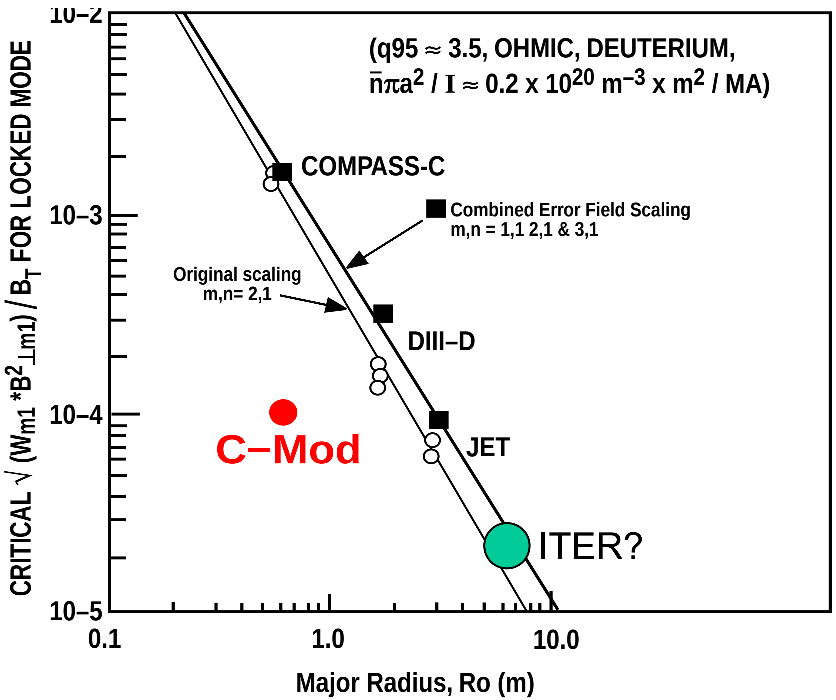
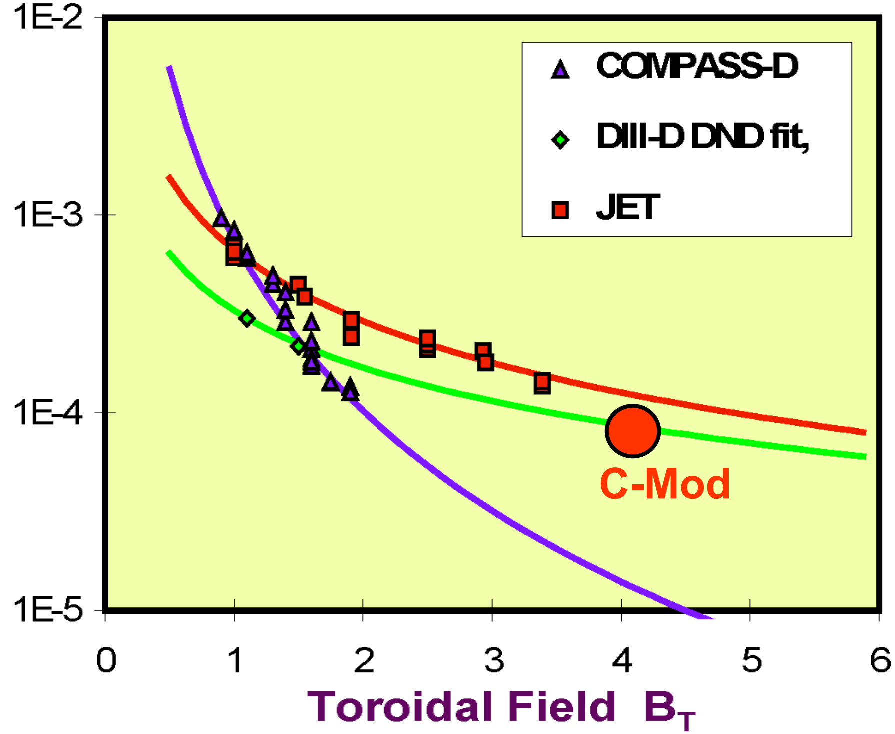
Size Scaling (LaHaye '97)



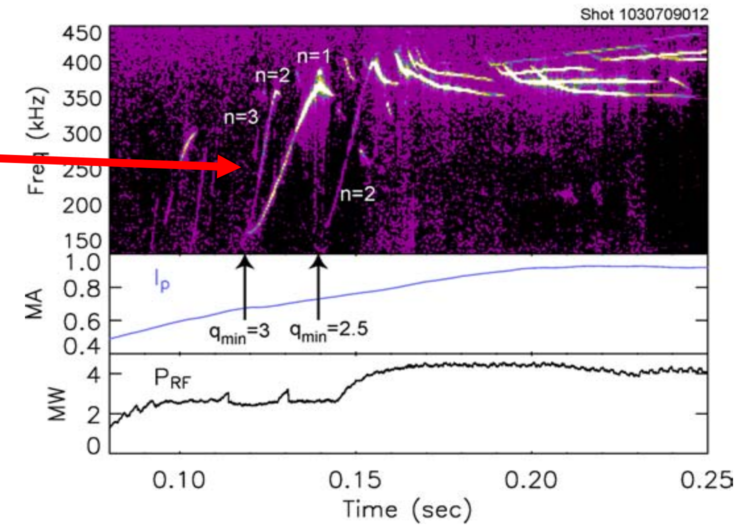
Toroidal Field Scaling (Hender, LaHaye)



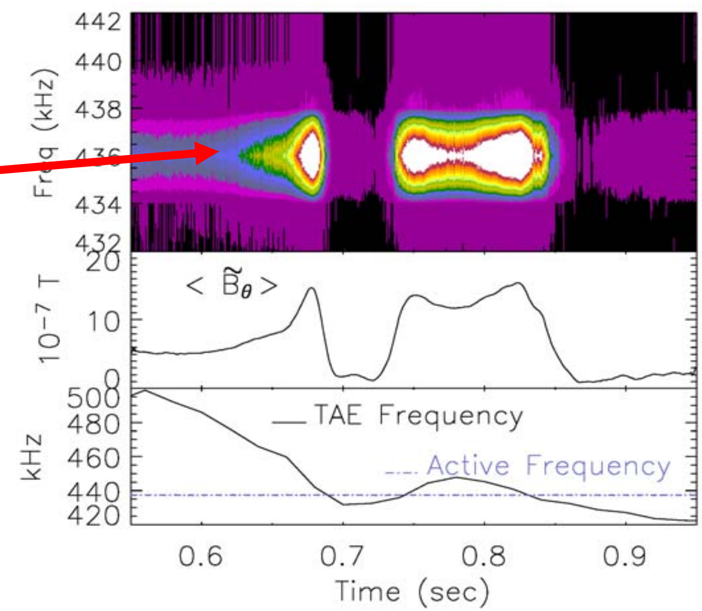
- Original size scaling pessimistic for ITER
  - C-Mod data implies much more optimistic extrapolation
- Toroidal field scalings very different on JET and Compass
  - Coordinated C-Mod/JET experiments planned to investigate B_T scaling (Identical dimensionless parameters)

Alfven Eigenmodes could be Important in Burning Plasmas

- Magnetics and Phase Contrast Imaging measurements reveal Alfven cascades
  - Fast ions from ICRF minority heating (E ~ 200 keV)
  - Can also be used as q_{min} diagnostic with negative shear (as on JET)



- Active spectroscopy used to drive and study stable modes
  - Antenna optimized to drive moderate n~4, ITER relevant modes

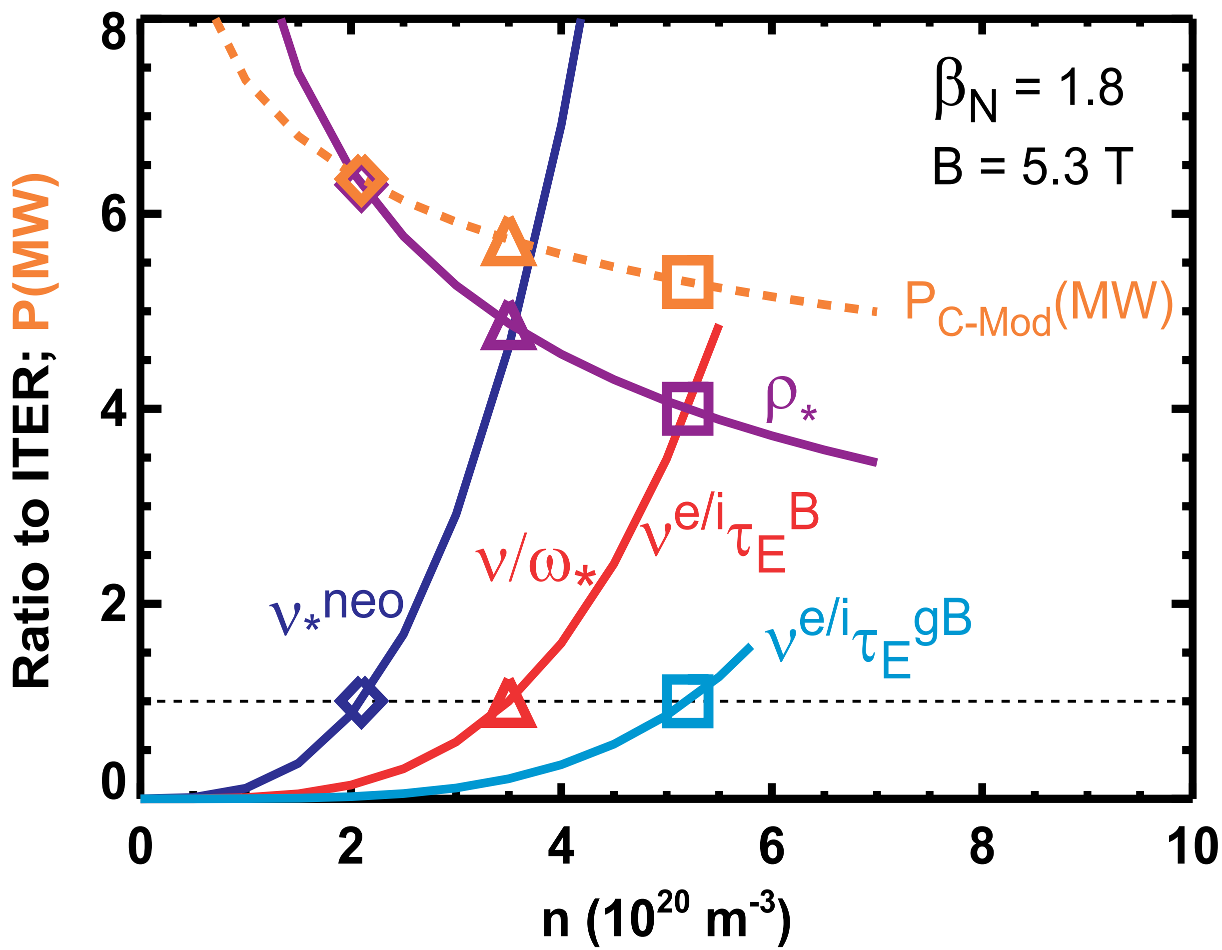


C-Mod accesses relevant non-dimensional *and* dimensional parameters for ITER

Alcator C-Mod

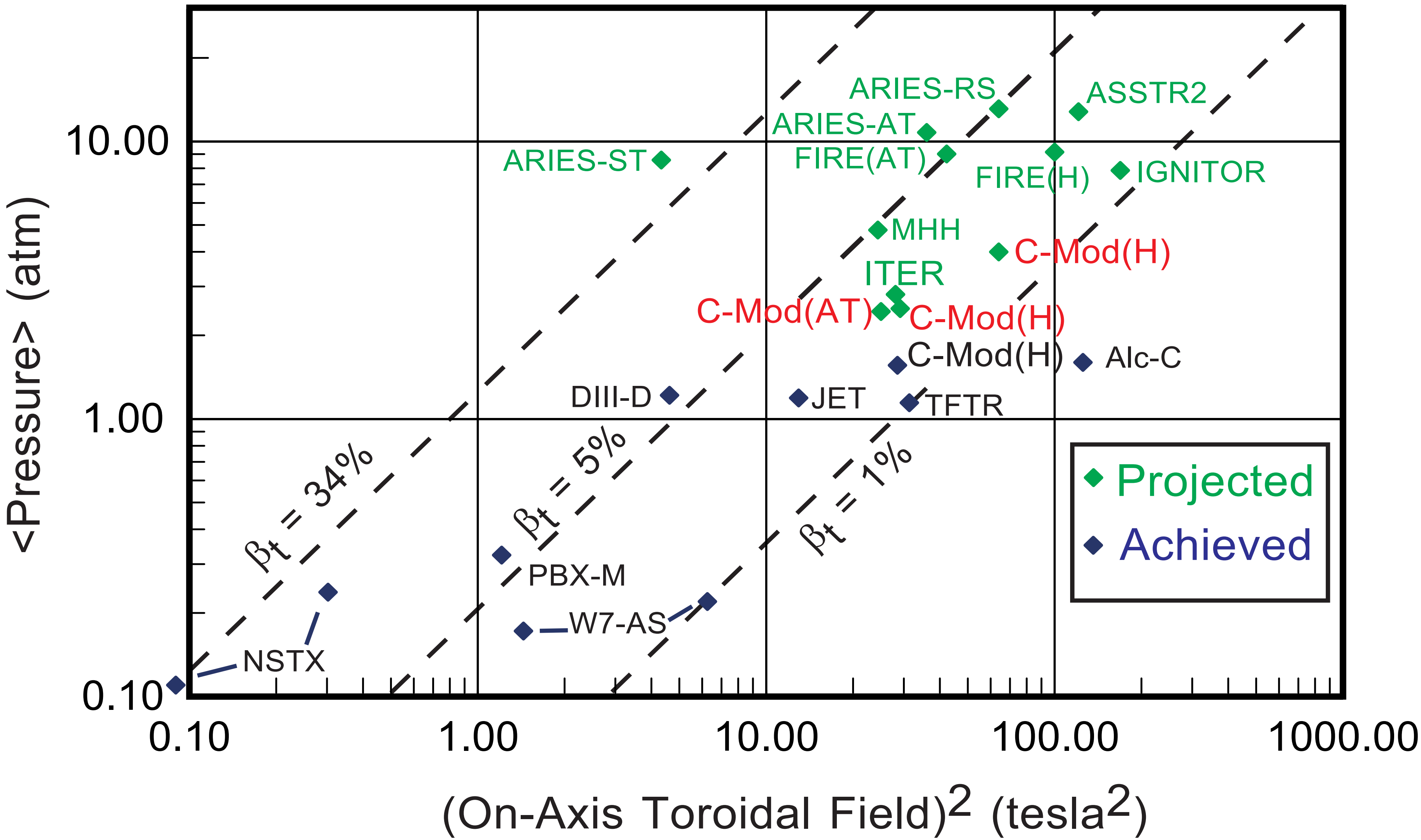
- Standard operation at 5.3 Tesla
- Matches β *and* absolute pressure
- Gyrosize:

  $4 \leq (\rho_*/\rho_*^{ITER}) \leq 6.5$
- Different collisionalities for different physics



C-Mod should reach ITER pressure at same β
Power reactors require higher pressure

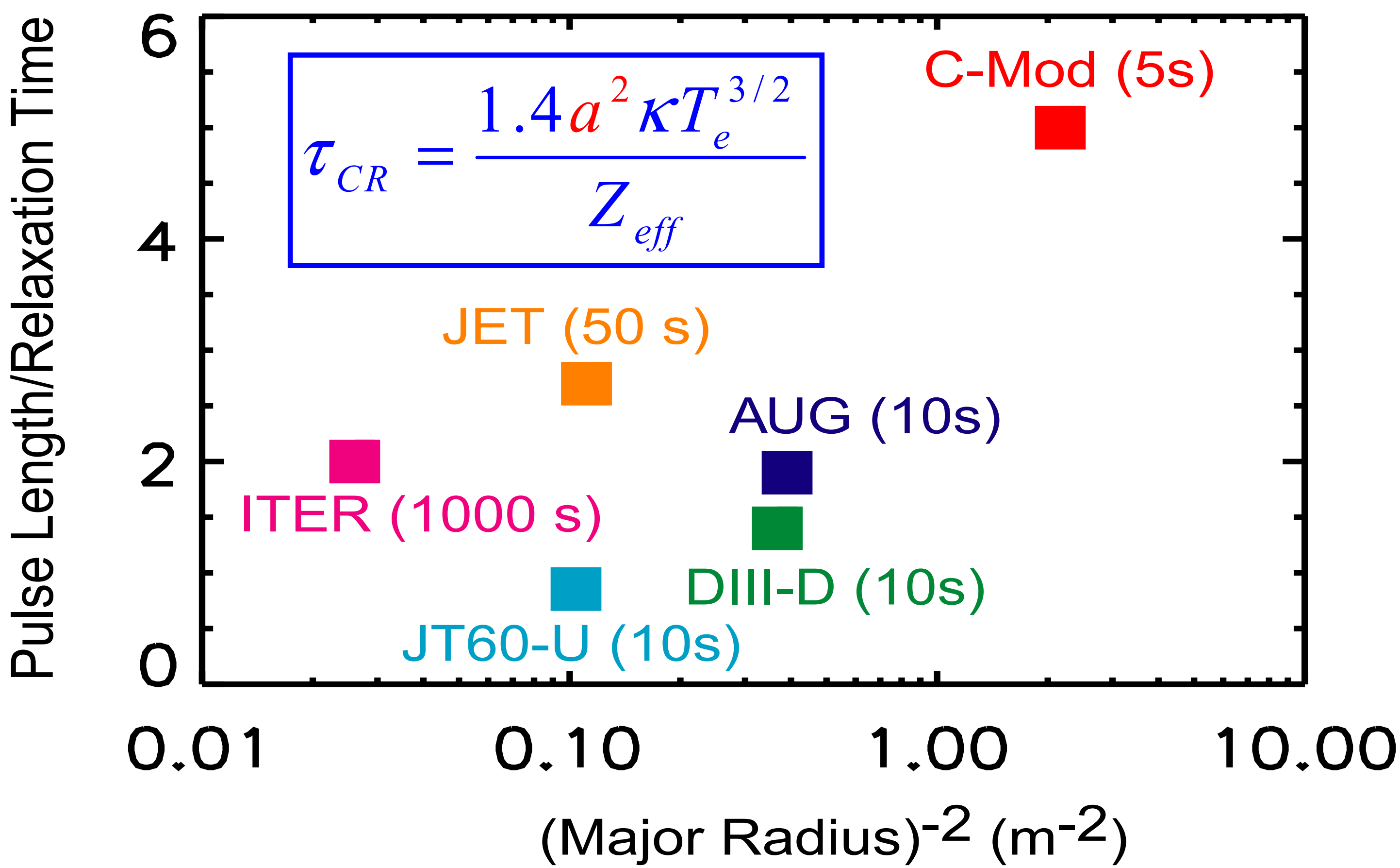
Alcator C-Mod



Tokamak Power Reactor requires Advanced Features

Alcator C-Mod

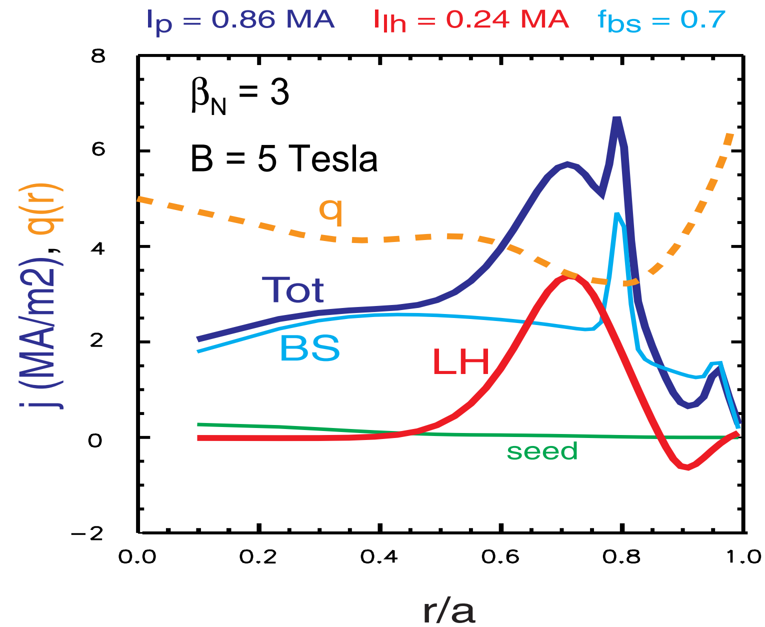
- Steady State
  - High bootstrap fraction + Efficient current drive
- C-Mod uniquely positioned to study fully relaxed current profiles



Lower Hybrid will be used for far Off-Axis Current Drive

Alcator C-Mod

- Far off-axis LHCD (4.6 GHz, 4 MW)
- Target plasma is fully non-inductive, at no-wall limit, 70% bootstrap fraction
- First experiments: Spring 2004



Klystrons installed in experimental cell

Unique C-Mod Capabilities
⇒ Address Key Questions: Next Step Burning Plasmas

Alcator C-Mod

- Unique dimensional parameters (B/R, Power/Area, Plasma Pressure)
  - Key points on scaling curves
  - Tests non-similar processes through Dimensionless Identity experiments (neutrals, radiation, …)
  - Pedestal structure and regulation
- Equilibrated electrons and ions
- Very high SOL power density, all-metal Plasma Facing Components
  - Reactor relevant regime
  - Unique recycling properties, D/T retention
- Reactor-like normalized neutral mean free path (depends only on B)
- Prototypical disruption forces
  - ITER level plasma pressure, energy density (disruption mitigation)
- Exclusively RF driven
  - Heating decoupled from particle, momentum and current sources
  - Efficient off-axis current drive with Lower Hybrid
- Long pulse relative to skin and L/R times