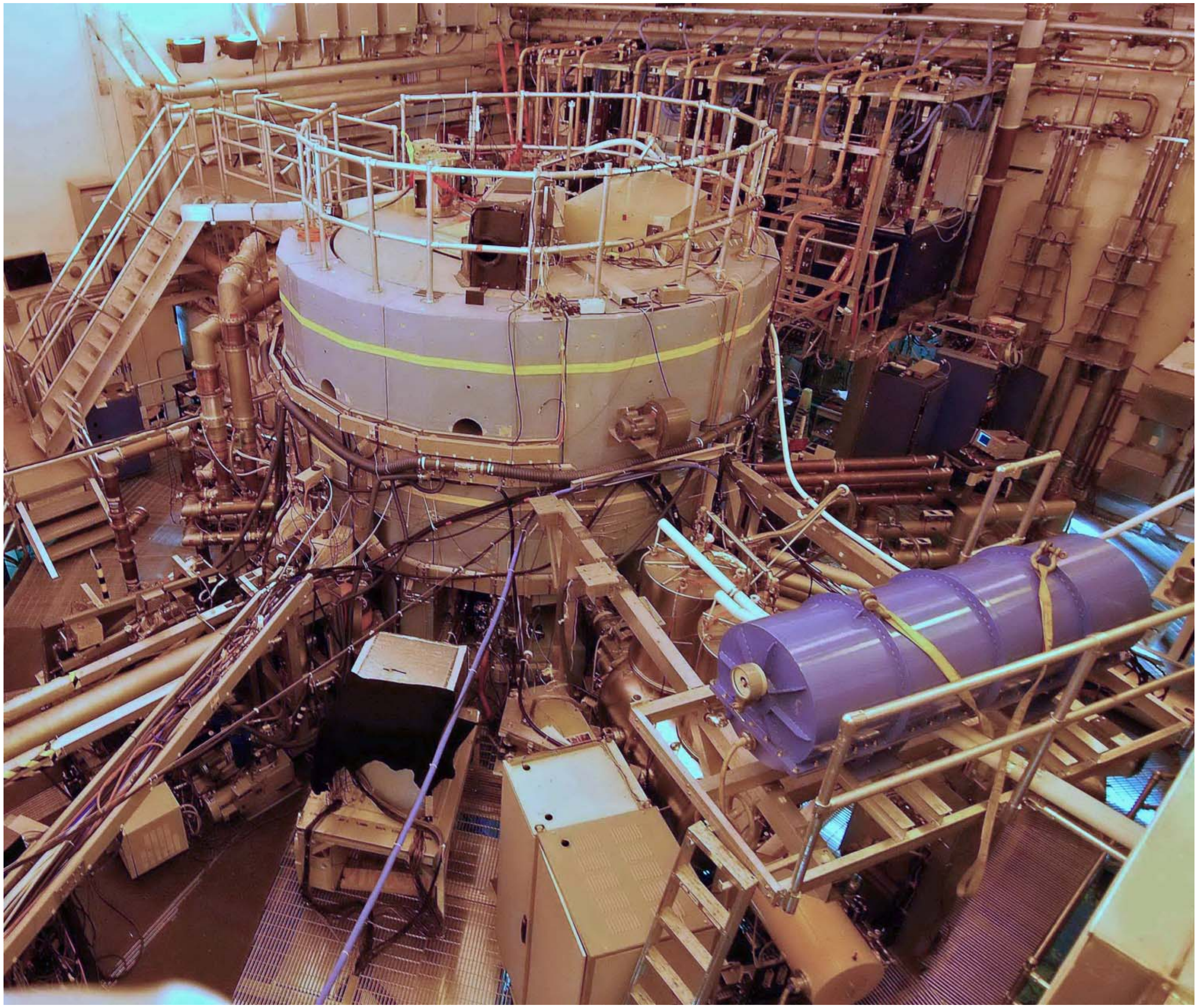
Alcator C-Mod Research Highlights and Plans



Presented by E. Marmar on behalf of the Alcator Team

FPA Annual Meeting

2 December 2009

Developing the steady state, high-Z wall, high-field tokamak for ITER and beyond

C-Mod research program focuses on areas of unique capability, ITER relevance

Alcator C-Mod

- **C-Mod restarted operation in June 2009 after a successful inspection of both machine and alternator.**
  - Many new diagnostics.
- **Broad science campaign, with particular emphasis on ITER needs and requests.**
- **Experiments exploit key C-Mod features,** eg.
  - Solid metal walls; Mo, W: D retention and recovery
  - High divertor heat fluxes: Power handling, impurity generation.
  - High density and neutral opacity: Pedestals and n_e control.
  - ICRF and LHCD at ITER B_T, density: H&CD physics
  - High pressure (<P> up to 1.8 atm): Disruption mitigation
- Graduate students are key, integral members of the scientific team
  - Currently 32 full time doing their PhD research on C-Mod
- **Strong emphasis on comparison of detailed measurements with simulations**.

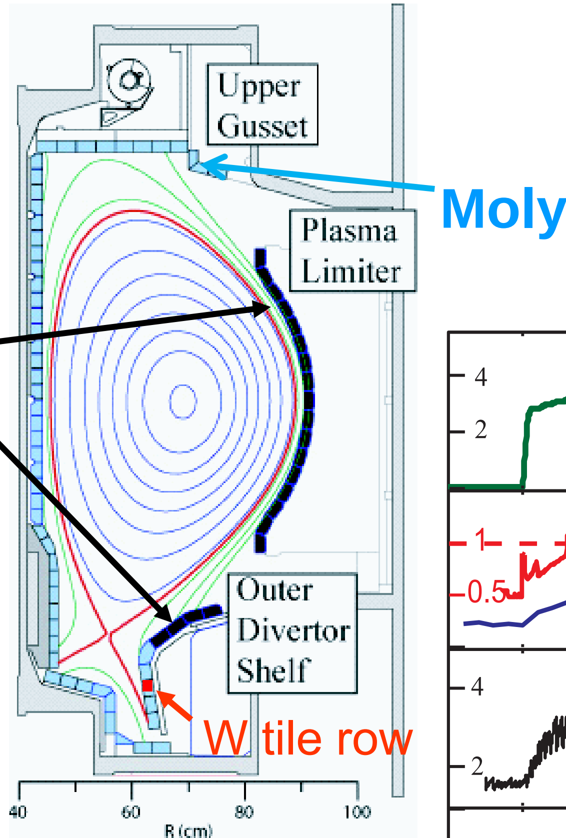
Recent Research Highlights

Alcator C-Mod

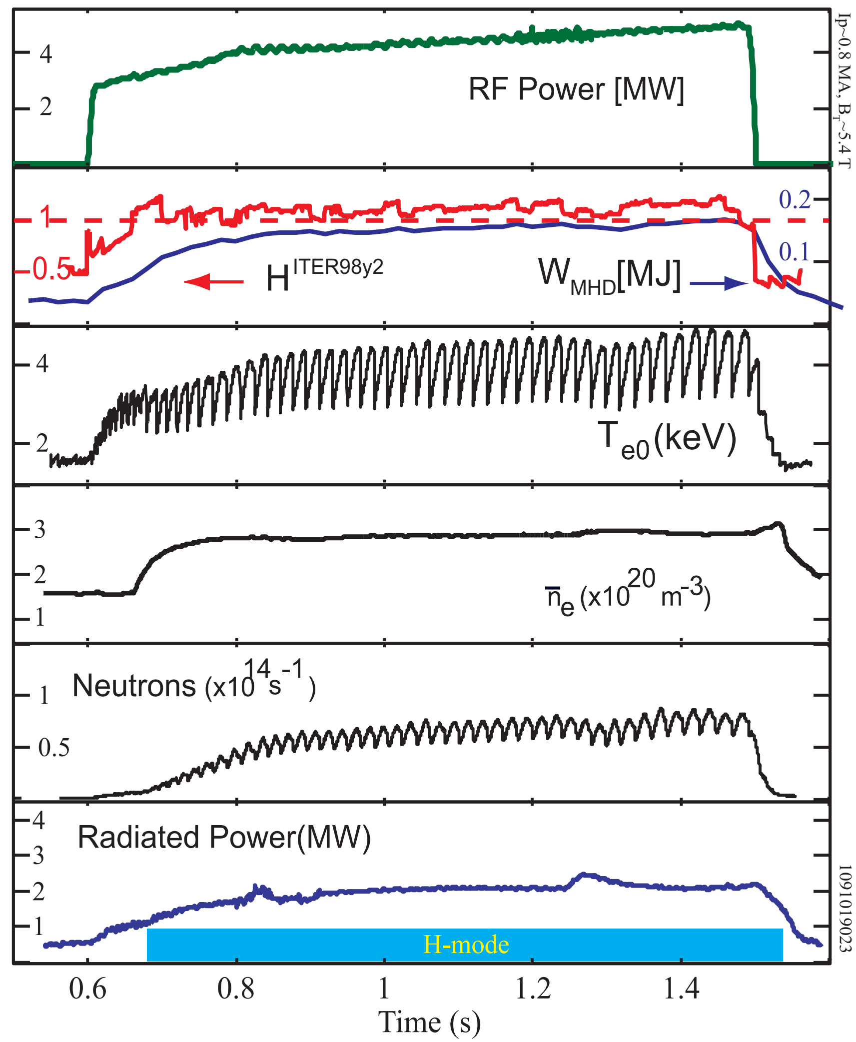
- Many new and interesting results from recent research operations
  - Hydrogenic retention
  - Improved confinement "`I-mode`"
  - Neon and nitrogen seeded plasmas (all regimes)
  - H-mode pedestal physics
  - Disruption mitigation
  - B-coated Mo tile operation
  - ITER discharge development
  - Edge turbulence
  - Gyro-kinetic modeling of core turbulence measurements
  - Modeling of Lower Hybrid coupling and propagation
  - SOL transport, divertor heat flux (FY10 joint research milestone)

Progress in handling high input power

- Impurity generation with RF heating, metal walls is a long-standing issue.
- **During torus opening, coated selected PFC tile areas with B to better understand RF erosion.**
- Reduced Mo influx ~10X, extended the RF energy input between boronizations (to ~100 MJ).

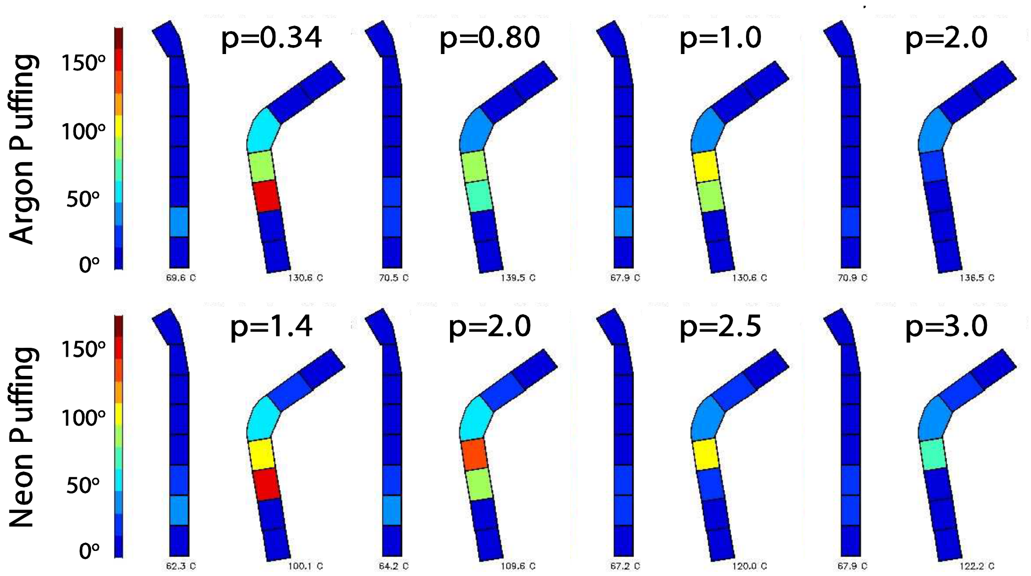


- Many experiments this campaign used high power (4-6 MW) ICRF.
- At these high heat fluxes, divertor tile heating becomes an issue.
- **Impurity seeding (Neon or N) was found to reduce T_{div}, prevent high Z injections, while maintaining good H-mode confinement** (as is hoped on ITER).



Seeding reduced divertor tile heating, and impurity injections.

Divertor temperature rise



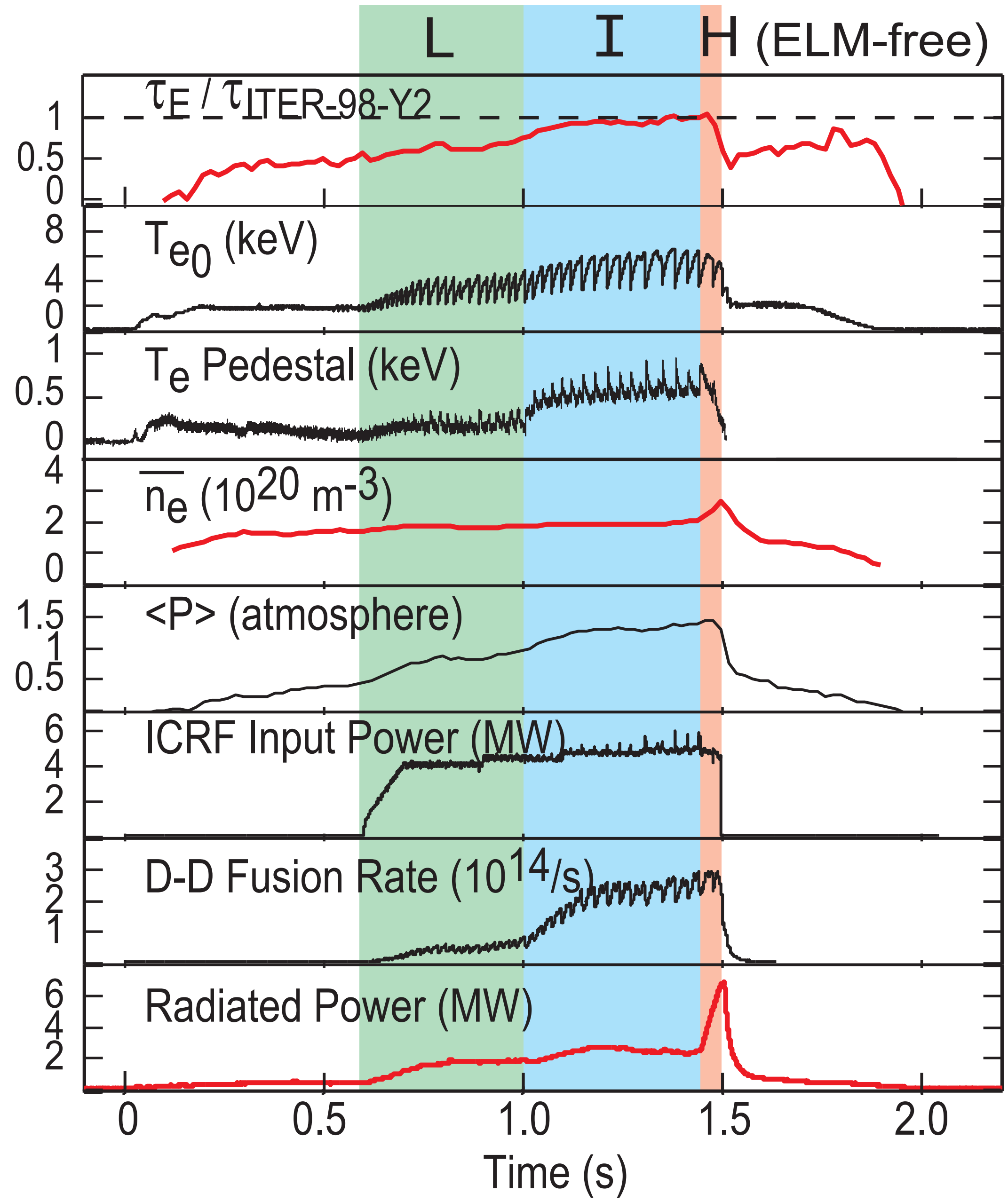
increased seeding →

- **With either Argon or Neon, seeding greatly reduces peak divertor tile temperatures.**
- **Also eliminates high Z impurity injections, which can be a problem due to extremely high power density on C-Mod. This reduces ICRF trips.**
- **Net result can be higher performance H-modes with Neon seeding – starting to use in other high power experiments.**

I-mode: H-mode Energy Confinement, L-mode Particle Confinement

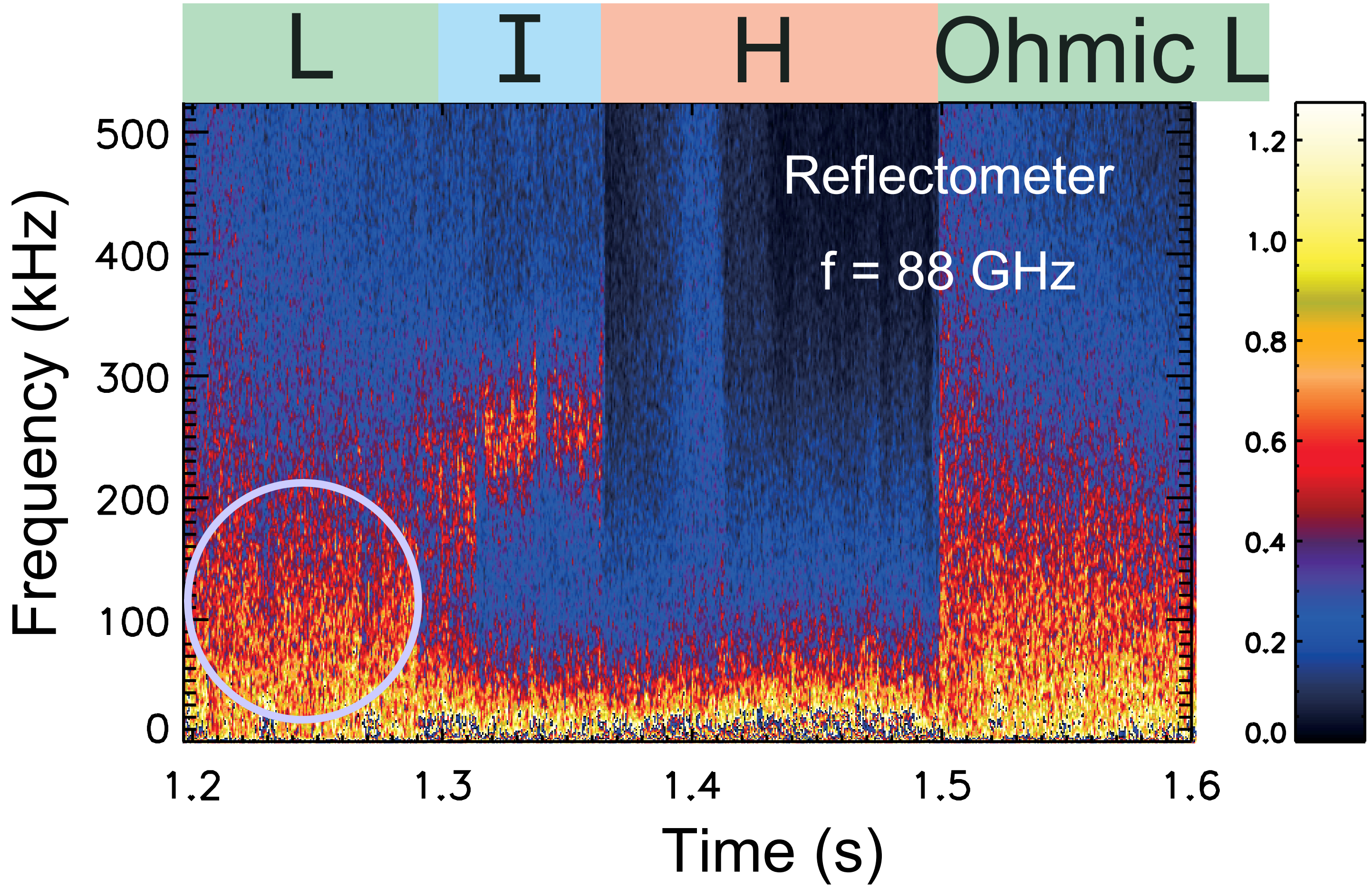
- Obtained with unfavorable drift (high L-H thresholds)*
- Globally, the regime is characterized by high energy confinement, often matching H-mode scaling (H_{98y2} ~1.)
- But, no particle barrier or impurity accumulation
  - With cryopumping, density can be controlled at the level of the ohmic target
  - P_{rad} stays very low.
- Does not require recent boronization
- Compatible with low Z impurity seeding

B=5.6 T, I_p=1.2 MA, q_{95}=3.3



*See Ryter, et al., PPCF **40**(1998)725.

Edge/Pedestal Density and Magnetics Fluctuations in L-, I- and H-mode



- L-mode: broadband fluctuations (50 – 200 kHz) drive energy and particle transport
- I-mode: broad band reduced, ~200 kHz appears; particle transport similar to L, energy transport suppressed
- ELM-free H-mode: ~200 kHz also gone, impurity accumulation

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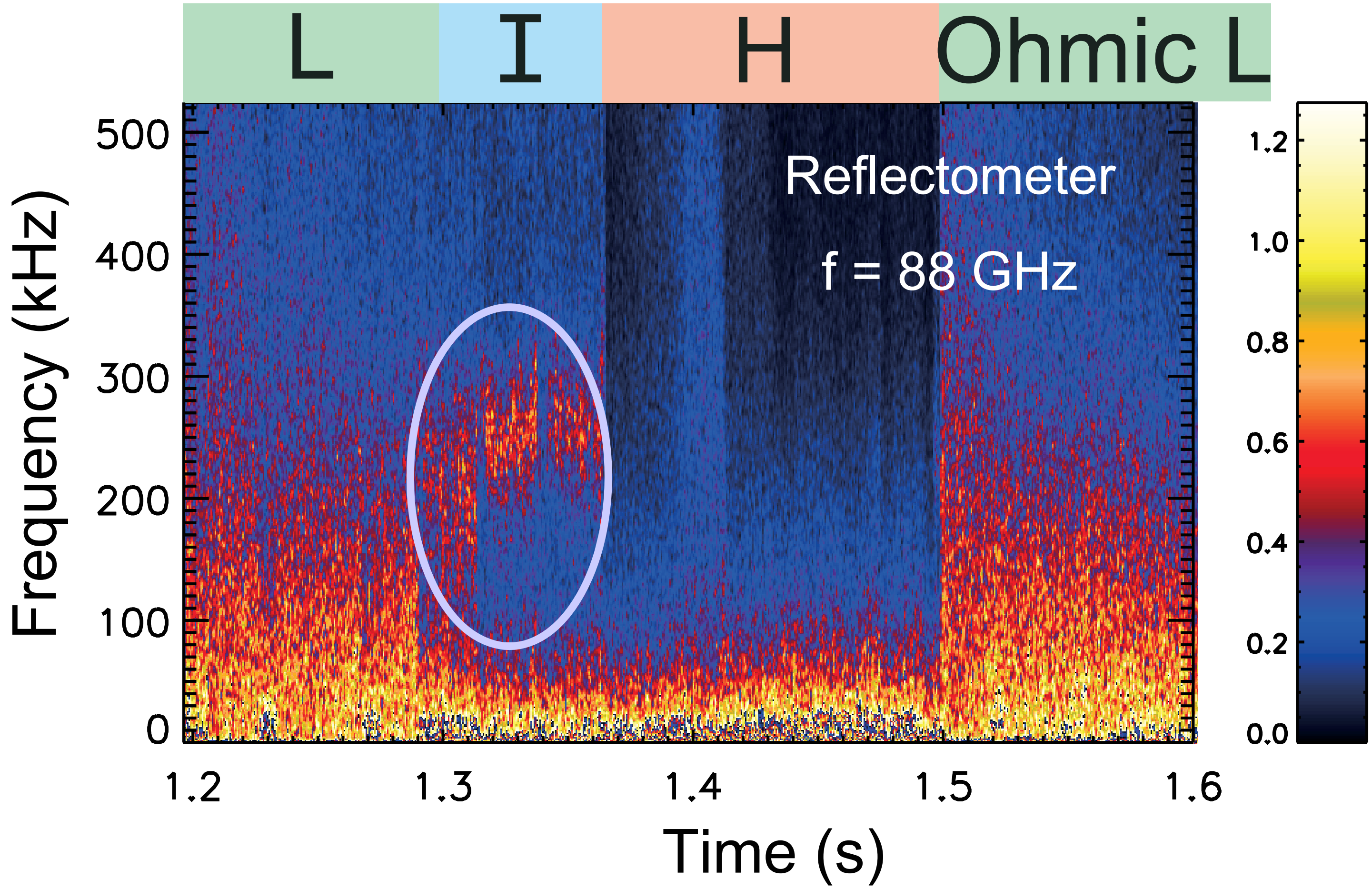

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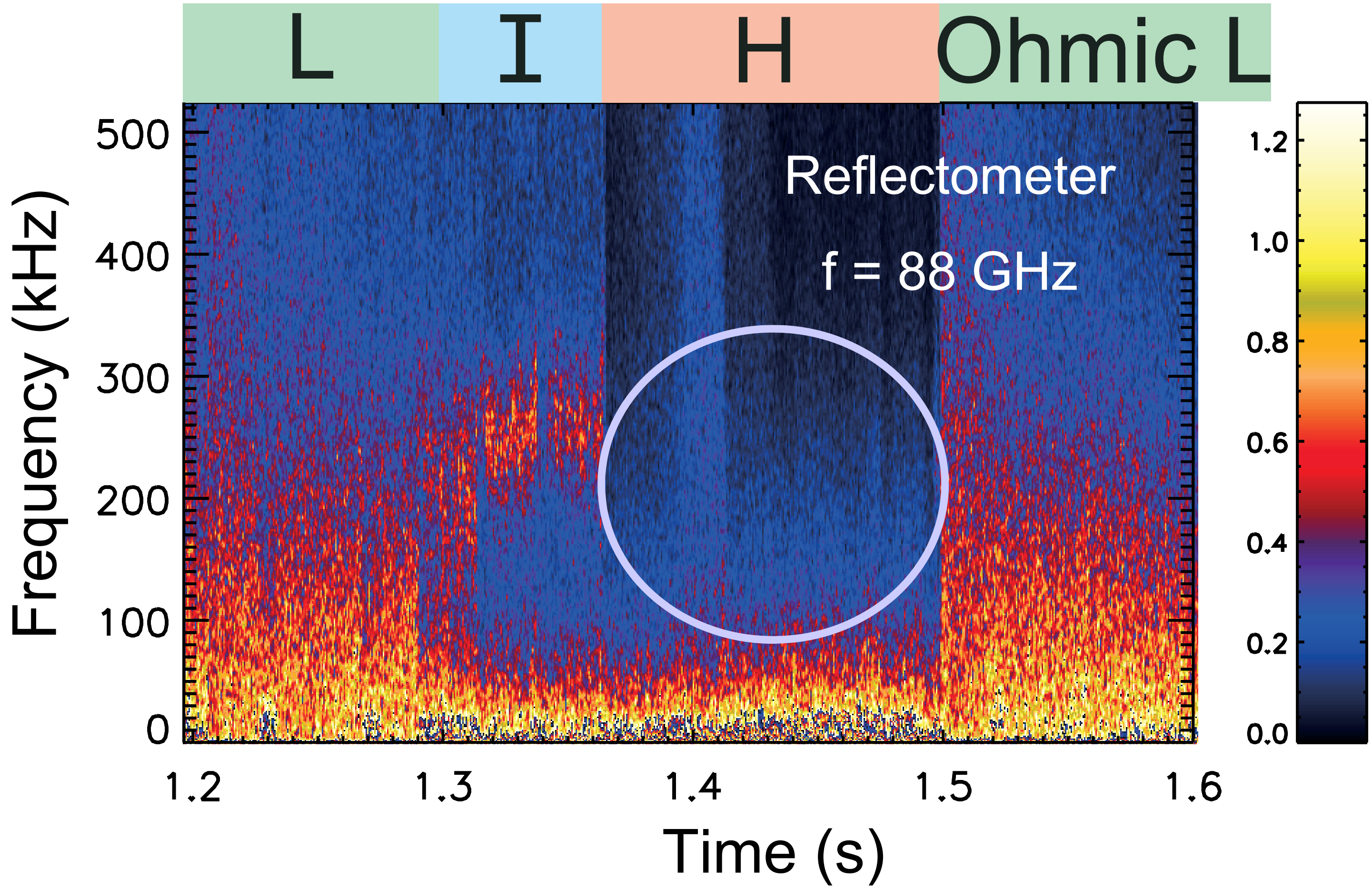

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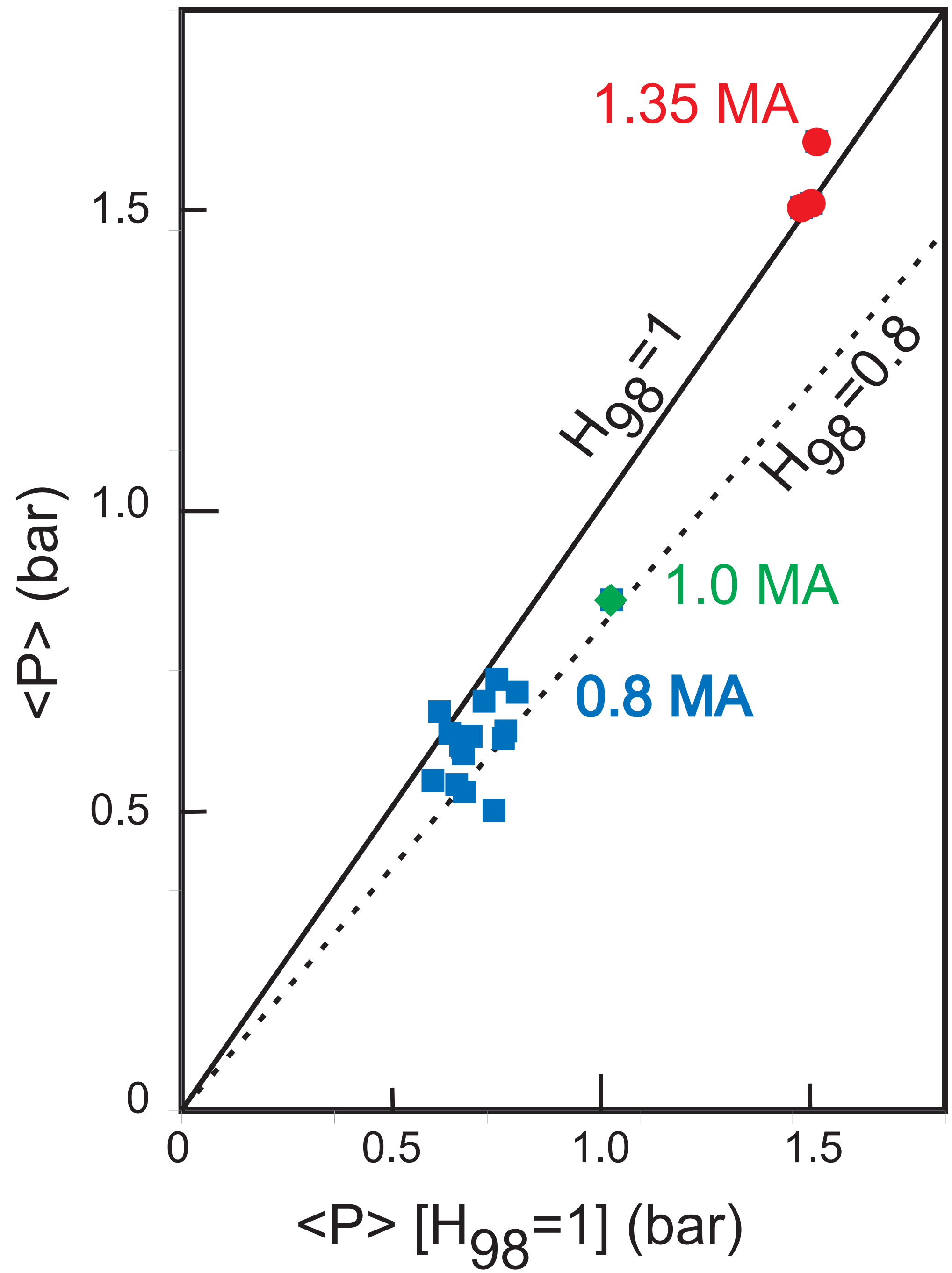
Parameter scans revealing operational space for I-mode

- Confinement quality improves at highest pressures (power, current)
  - But need to stay out of H-mode (density barrier)
- With unfavorable drift, H-mode threshold appears highest with a combination of
  - Low q_{95} (<3.5)
  - Strong shaping
- ELMs not required for edge particle regulation
- Interest in exploring application to ITER
  - alternate regime in case of difficulties with H-mode or ELM control



Parameter scans revealing operational space for I-mode

Alcator C-Mod

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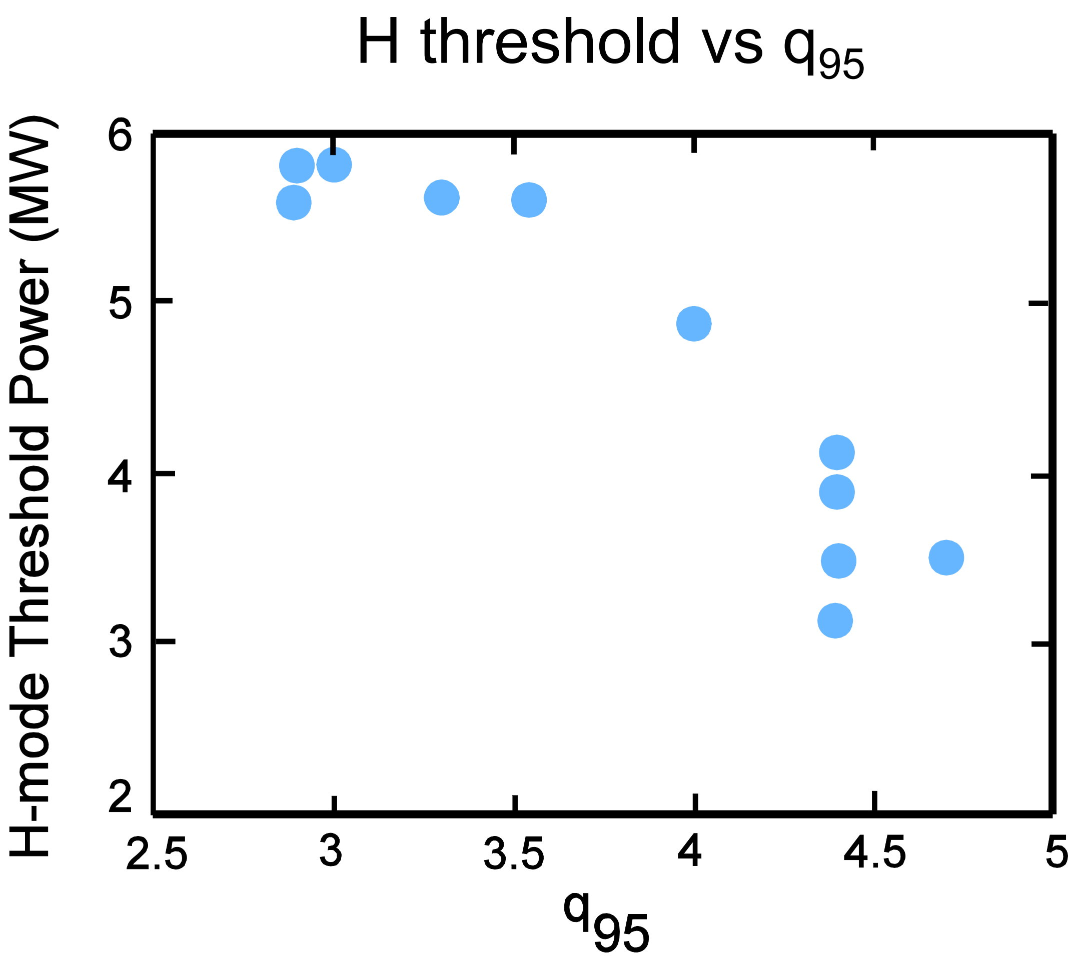
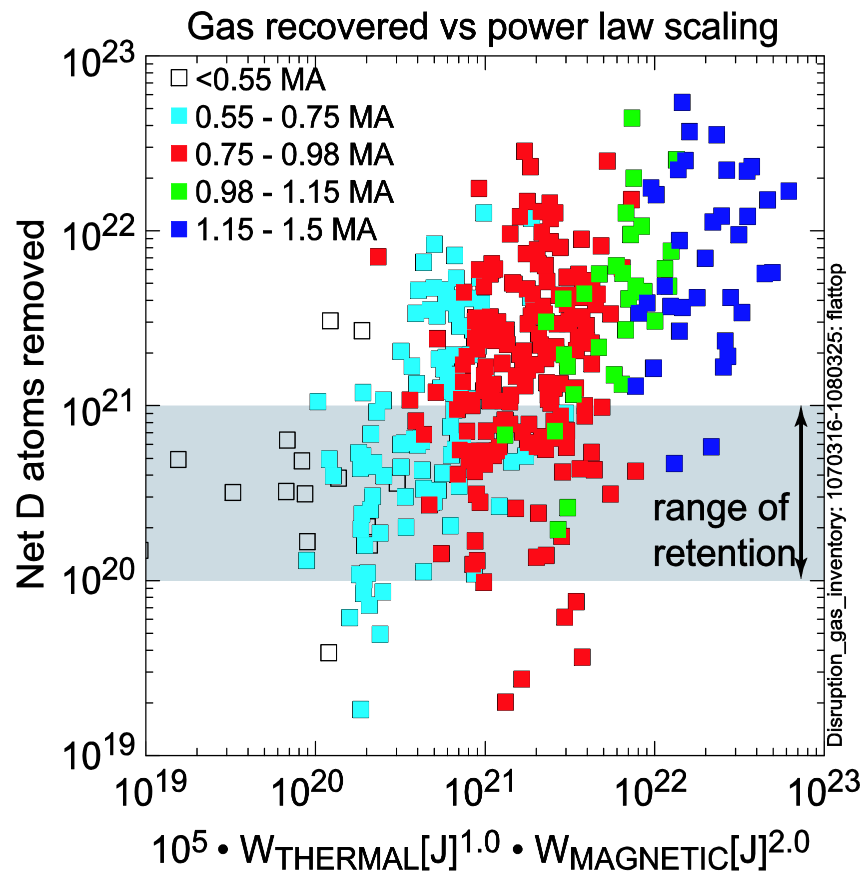
  - But need to stay out of H-mode (density barrier)
- With unfavorable drift, H-mode threshold appears highest with a combination of
  - Low q_{95} (<3.5)
  - Strong shaping
  - As high as 4x the ITER scaling for threshold with normal drift
- ELMs not required for edge particle regulation
- Interest in exploring application to ITER
  - alternate regime in case of difficulties with H-mode or ELM control



Significant recovery of D from metal walls following disruptions

- Past C-Mod experiments showed unexpectedly high retention of D in Mo, W PFCs
  - 1-2% in single discharges, comparable to C.
  - But, campaign-integrated retention is ~1000x lower.
- Large release of retained gas following disruptions.
  - Scaling with magnetic energy ($\sim W_{MAG}^2$) is stronger than with thermal energy ($\sim W_{TH}$).
- Results are consistent with ‘flash heating’ of key surfaces, underscoring the crucial role of wall temperature in retention.

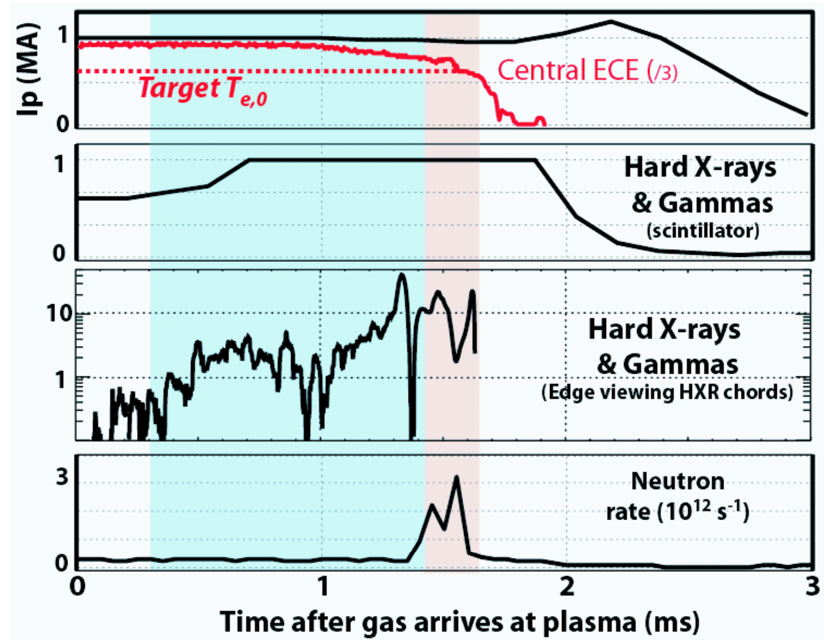


Scaling of C-Mod results to ITER suggests that reduced energy (~20 MJ) disruptions could release substantial T.

Rapid loss of runaway electrons during gas-jet-mitigated disruptions

Alcator C-Mod

- Massive Gas Injection disruption mitigation is optimized by He/Ar mixtures.
- Experiments with fast electron seeding by LHCD show rapid loss of runaway electrons during the thermal quench.
- NIMROD modeling (Val Izzo) shows stochastic fields cause rapid loss.

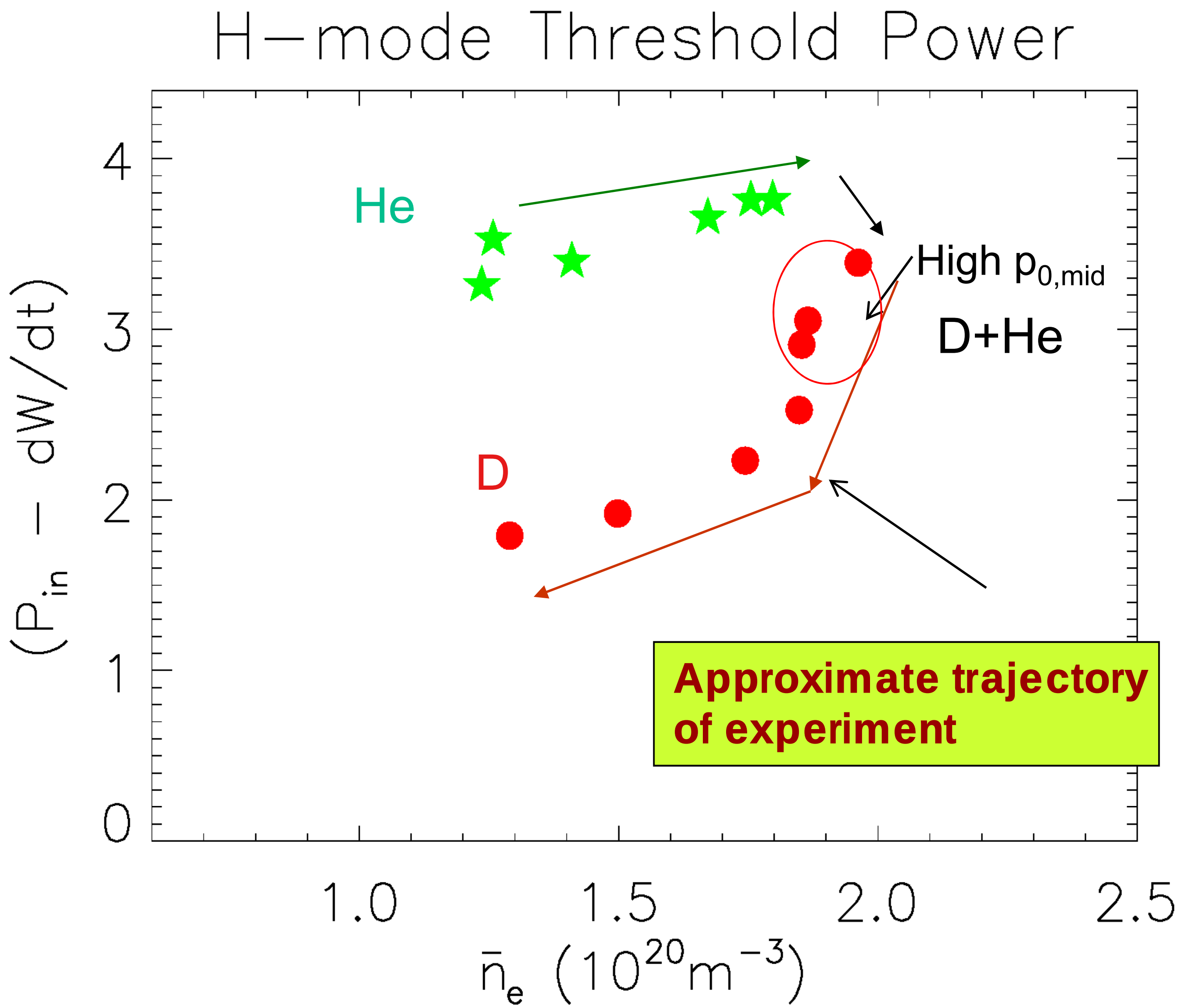


Results imply it is not necessary to attain the Connor-Hastie-Rosenbluth collisional limit to suppress runaways.

- Radiation measurements integrated over the disruption show a toroidal asymmetry between chords looking at and away from the gas jet; variable, up to 2.5.
  - A concern for ITER due to potential melting of Be.

H-mode P_{thresh} Significantly Higher in He than D

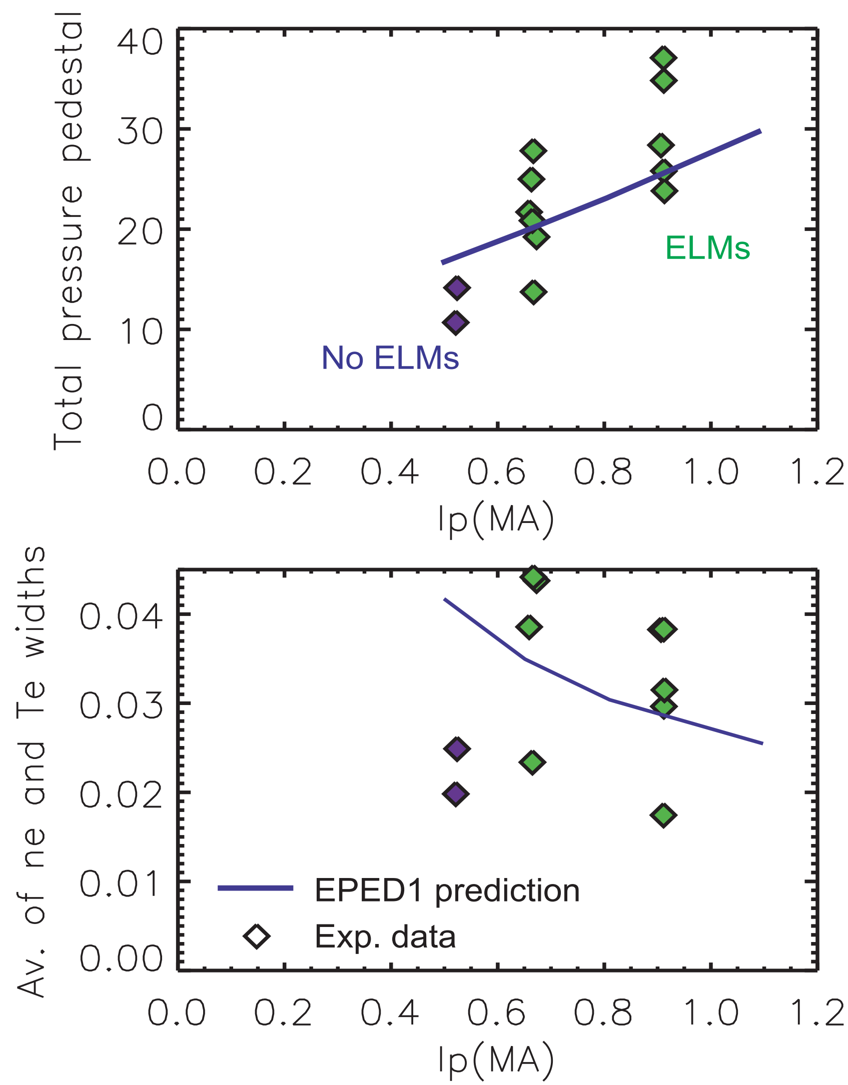
- In ITER pre-nuclear phase, helium operation proposed to explore H-mode
- On C-Mod, see significant increase in threshold for He
- $P_{th,He}/P_{th,D}$~1.2—1.8
- Comparisons with results from other facilities (JET, DIII-D, NSTX, MAST) ongoing through ITPA



J. Snipes, ITER Organization

EPED1* Simulations of H-mode Pedestal Showing ~Agreement with Experiment

- Mix of ELMy, EDA H-modes
- Pedestal profiles obtained from time-averaging Thomson points during steady H-mode phases
- Initial EPED1 calculations (blue curves) made before the experiment predict maximum pedestal height and width (just prior to ELMs)
  - EPED1 predictions need to be revised based on actual beta and density obtained in experiment
- C-Mod contributions are expected to be especially useful in refining the next version(s) of EPED

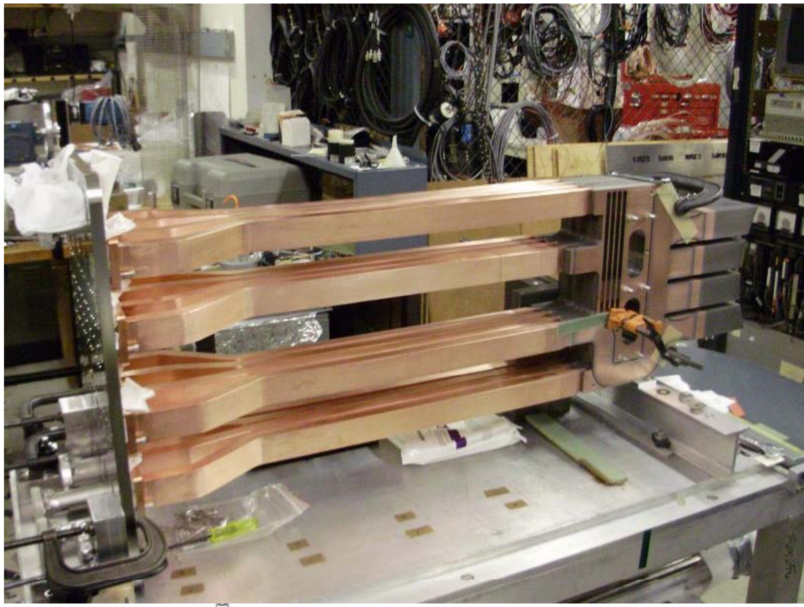


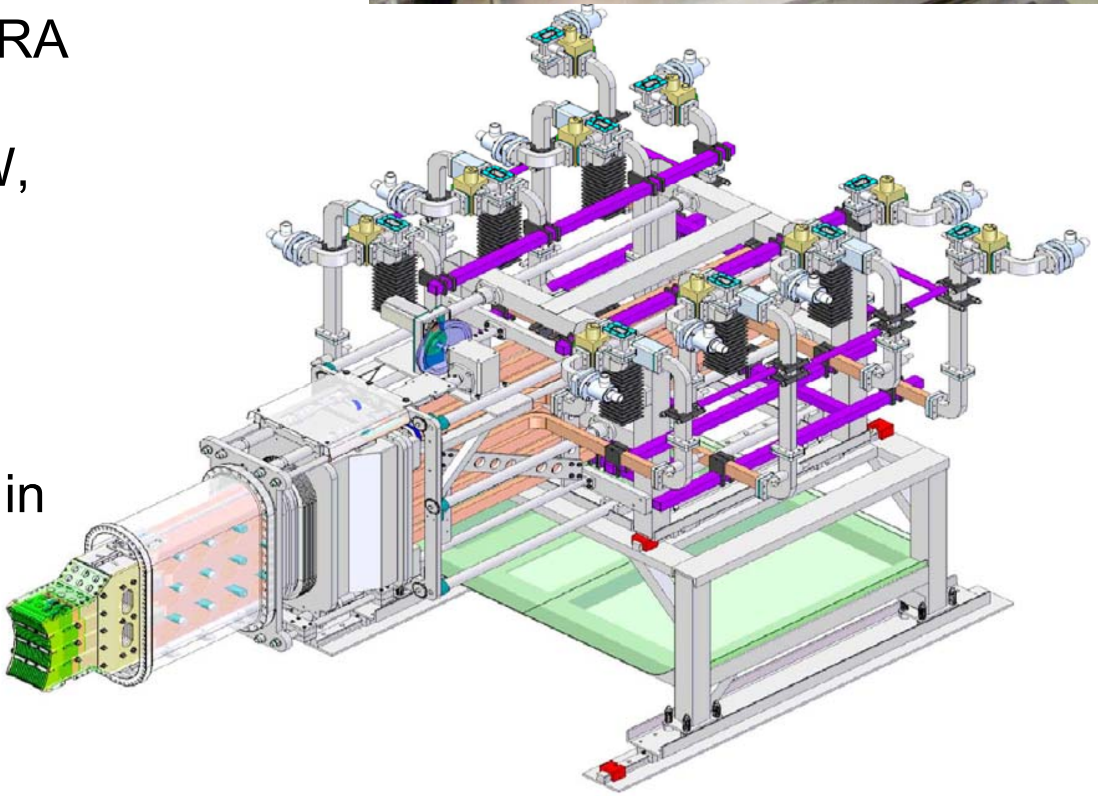
*Collaboration with P. Snyder, GA

Advanced low-loss Lower Hybrid launcher

Alcator C-Mod

- Launcher upgrade
  - Low loss waveguide from the klystrons to the splitter
  - Expect up to 70% of source power to reach the vacuum interface
  - Uses novel load-tolerant 4-way splitters
- Upgrading source power (ARRA funded)
  - 7 new klystrons (≥ 250 kW, CW)
  - Adding 4th cart
  - Will bring total installed power to 4 MW
- New launcher being installed in December

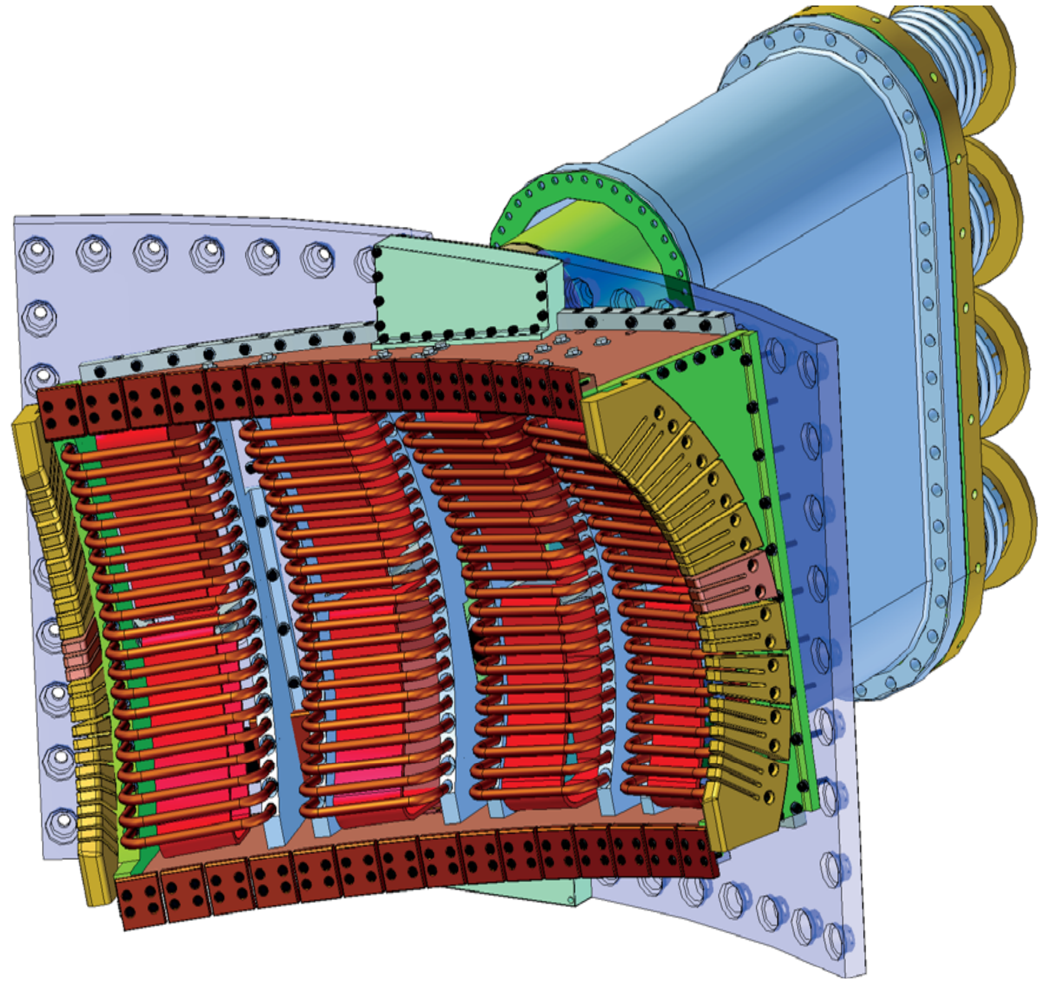




Field-aligned ICRF antenna designed to reduce RF Sheath induced sputtering

Alcator C-Mod

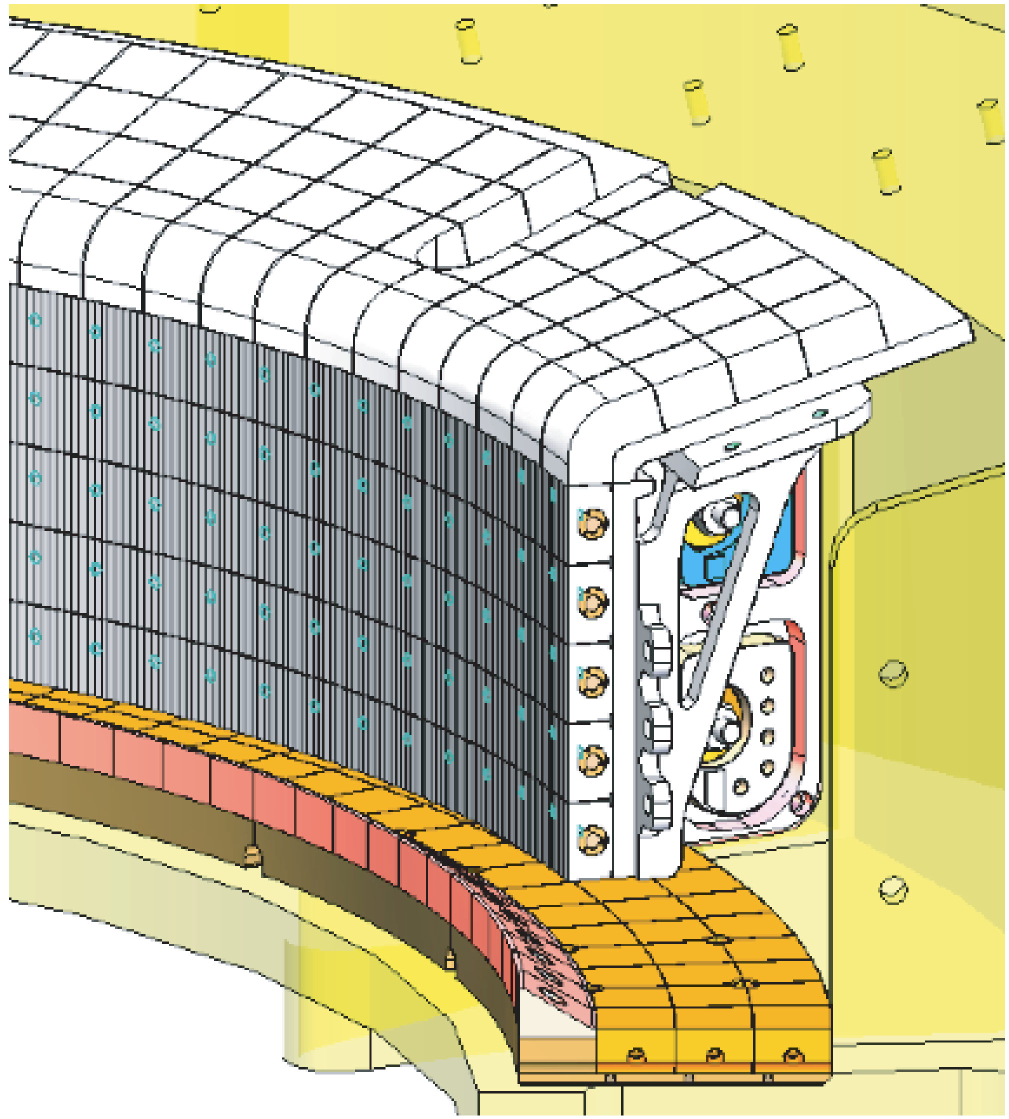
- ICRF induced sheaths implicated in high-Z impurity source production
- Rotating the antenna so that straps are perpendicular to local B
  - Modeling indicates substantial reduction of coupled $E_{||}$ (up to factor of 10 compared to vertical dipole).
- New antenna is in construction
  - Installation mid 2010



Advanced High Temperature Divertor

Motivation:

- Long Pulse - a new divertor design is required to extend the C-Mod pulse length (up to 5 seconds, 10 MW)
- High-Z studies and hydrogenic retention - an elevated operating temperature (up to ~600C) allows key exploration of:
  - Operational characteristics of tungsten
  - Fuel retention as a function of temperature.
- Both aspects drive the design toward a toroidally continuous, high-temperature divertor design.
- Joint effort with PPPL
  - Installation in FY2012



New Outer Divertor Conceptual Design

C-Mod FY2010 Campaign Well Underway

Alcator C-Mod

- Planning 18 total research weeks this fiscal year
  - Includes 5 weeks of incremental run-time funded through ARRA
    - Expect to complete the 5’th week tomorrow
- *New proposals and collaborations are always welcome!*