Operation of Alcator C-Mod with High-Z Plasma Facing Components: With and Without Boronization

Alcator C-Mod

- Operational experience with solid molybdenum Plasma Facing Components
- Effects of boronization
- Localized erosion of boron coatings
- Role of ICRF sheath enhancement

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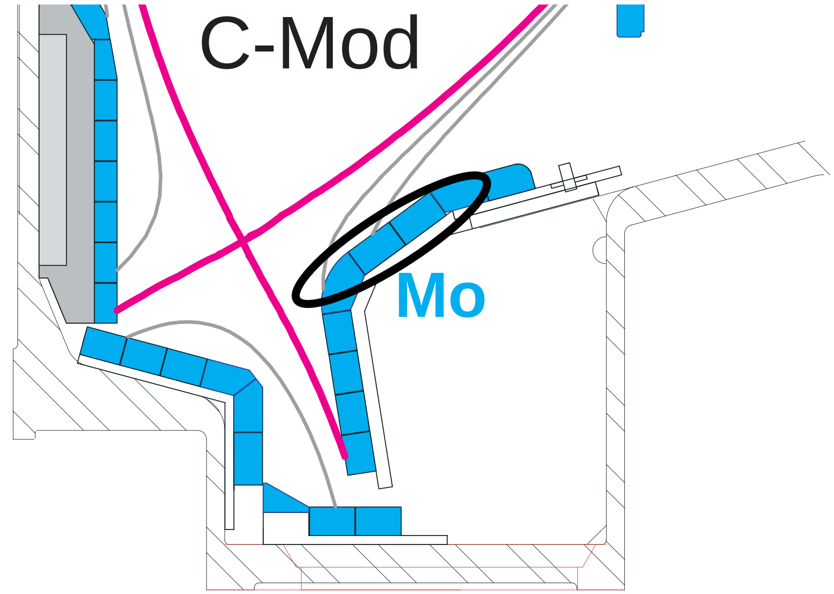
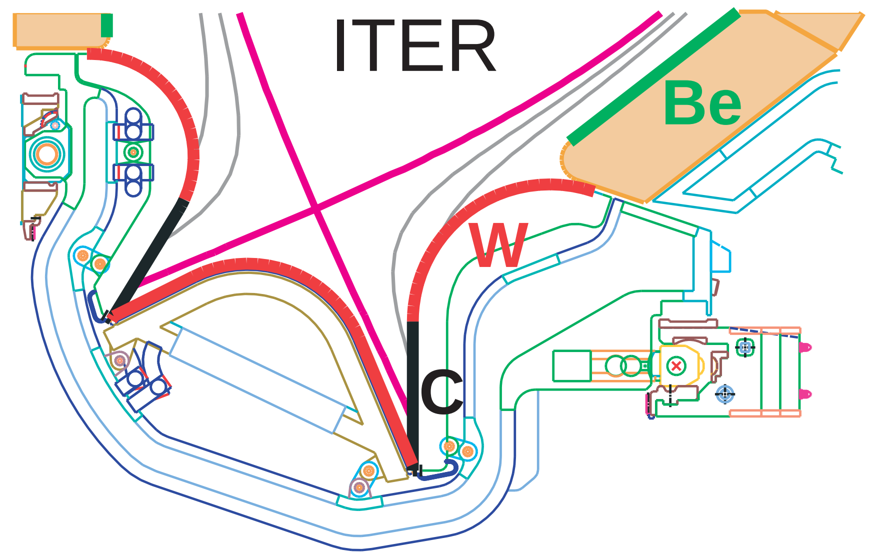
C-Mod very well Suited to Address High-Z PFC Issues

Alcator C-Mod

- C-Mod exclusively employs solid high-Z PFCs (Mo)
  - Mo very similar to tungsten (W)
    - Erosion
    - D retention
    - Radiation characteristics
- C-Mod divertor conditions can be equivalent to ITER
  - Power density, divertor n_e, T_e
  - SOL: opaque to neutrals, radiation
  - ICRF heating





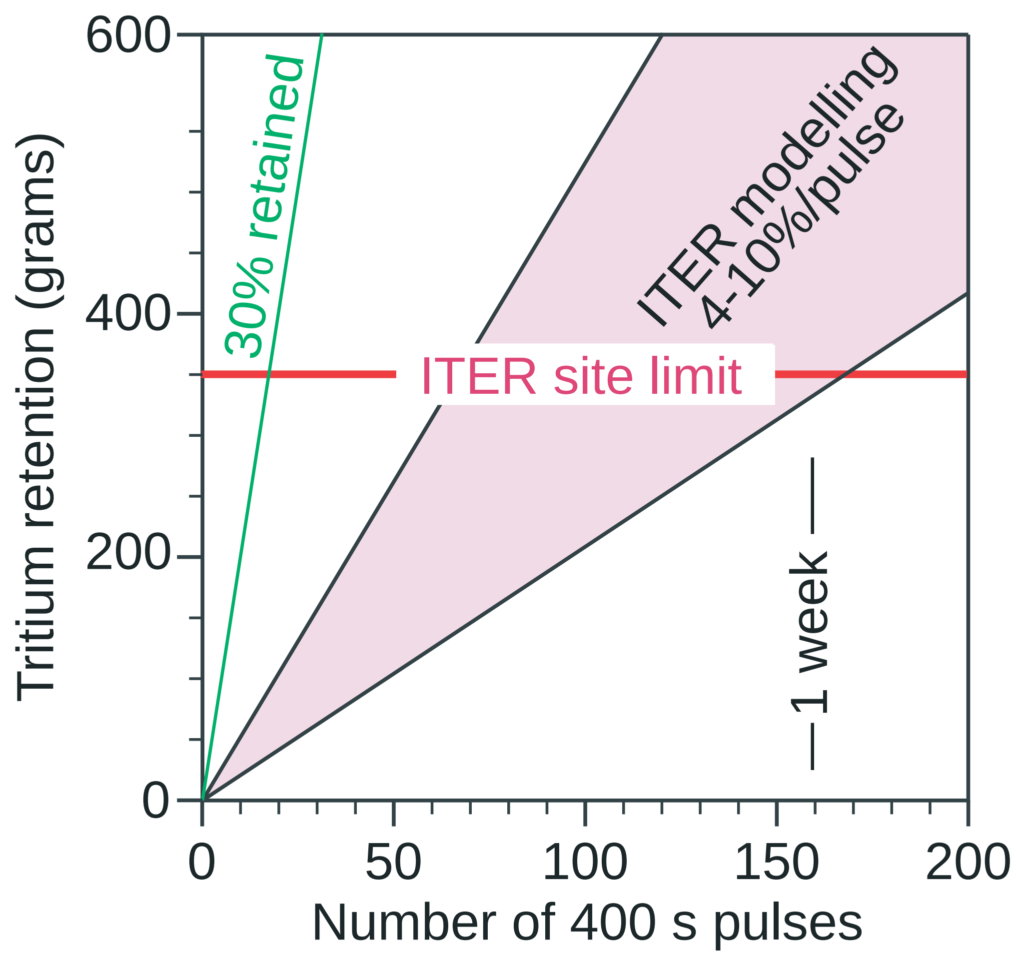
Report here on experiments comparing operation with uncoated and coated Mo

Why Care about High-Z?

Alcator C-Mod

- In ITER, serious concern about tritium retention (co-deposition with carbon)
- Looking beyond ITER, to reactors, additional issues
  - Erosion at first wall
  - Neutron damage to carbon-based materials
    - Drop in thermal conductivity
    - Material swelling
- Currently ITER plans to relegate carbon to small fraction of PFC surfaces
- Multiple studies have led reactor designers to choose tungsten

Simple extrapolation of tritium retention from JET and TFTR results (carbon PFCs)



High-Z has Advantages; Carries Risks

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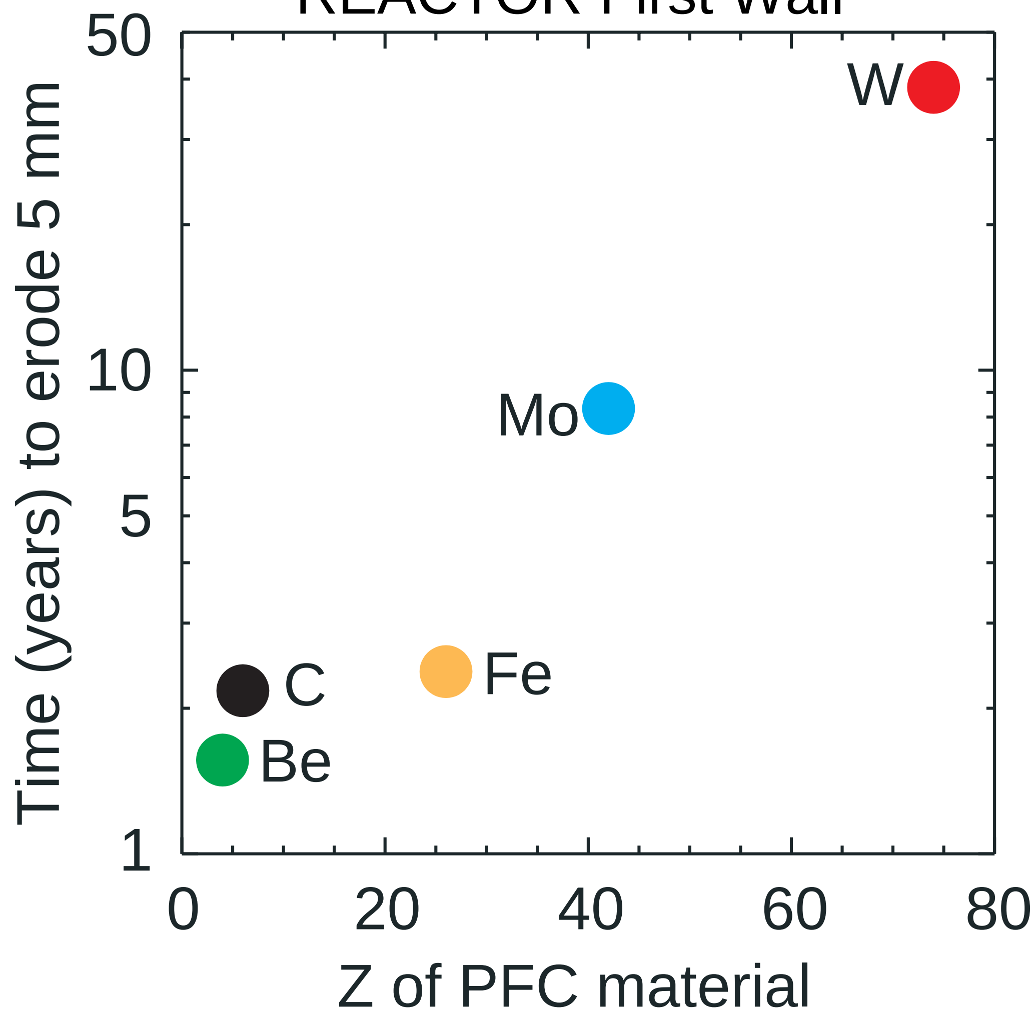
- Advantages
  - Very low erosion rate
  - Reasonable resistance to neutron damage
  - Low tritium retention (at least in some non-tokamak tests)
- Risks
  - Melting leads to enhanced heat loads
  - Allowable W concentration in the core plasma is very low (<10^{-5})
- Most of the world's divertor tokamak database developed using carbon PFCs*

Estimates of Erosion Rates for REACTOR First Wall

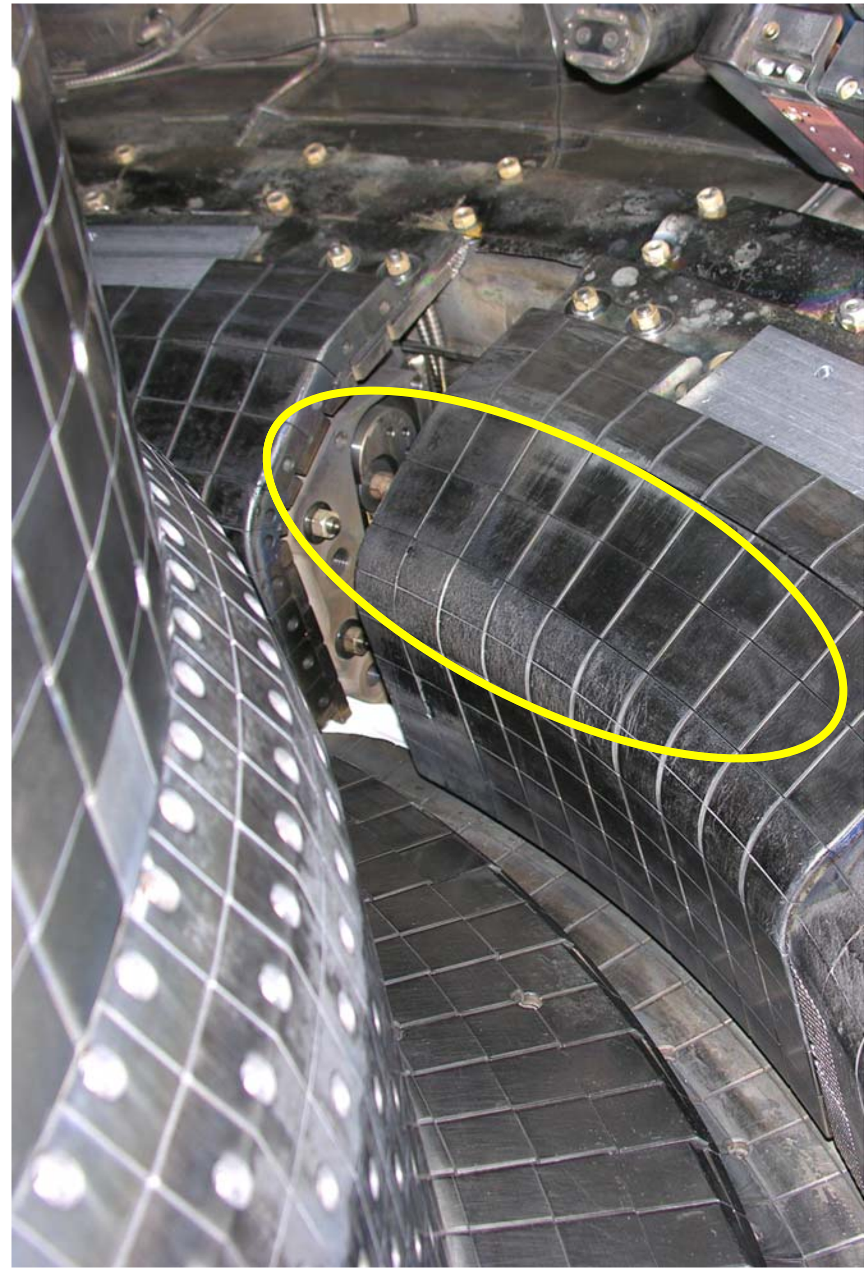


*ASDEX-Upgrade using W-coated graphite [Dux, previous talk]
JET planning to use W

Boronization used Routinely for Wall Conditioning

Alcator C-Mod

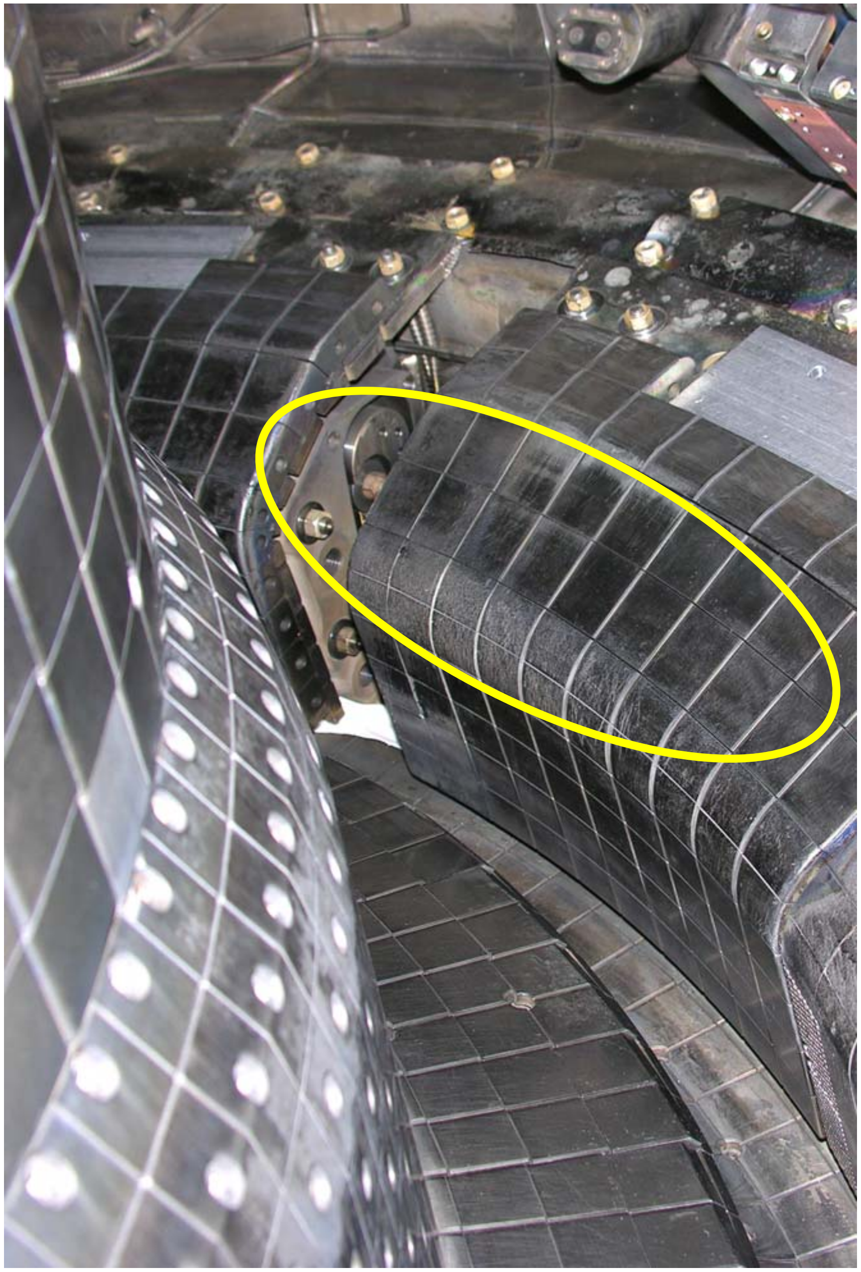
- Discharge cleaning and boronization accomplished using Electron Cyclotron resonance low temperature plasma Discharge (ECD)
- ECD parameters:
  - 2.5 kW, 2.45 GHz RF
  - Use toroidal field only; scan to move resonance from inner wall to beyond outer limiters ($B_{resonance}$=0.088 tesla)
  - T_e ~ 10 eV, T_i < 1 eV, n_e ~ 10^{16} m^{-3}
  - Cleaning using deuterium
  - Boronization using 10% B_2D_6 / 90% He
- ~10-hour boronization
  - average coverage of 200 nano-meter



Boronization used Routinely for Wall Conditioning

Alcator C-Mod

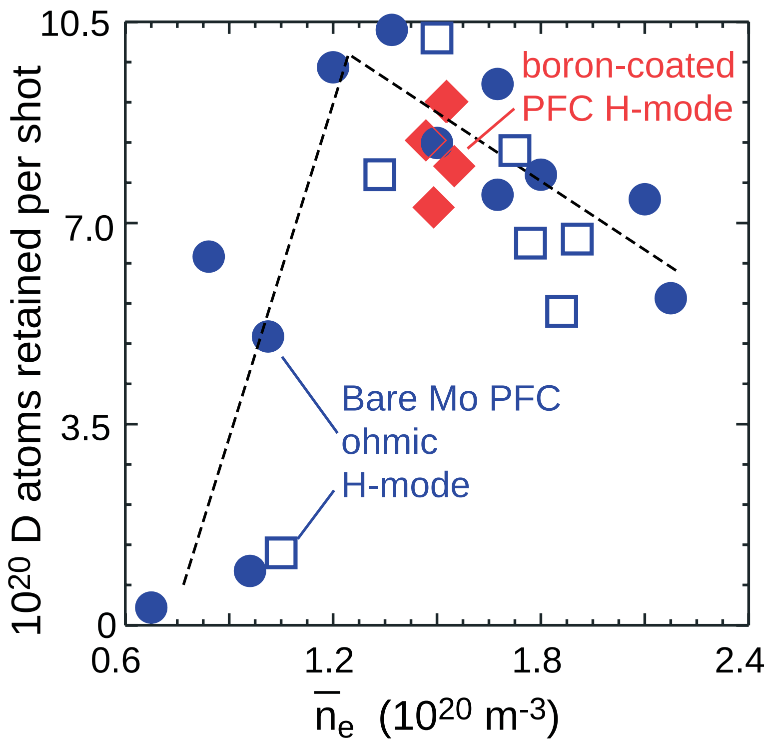
- Boronization employed almost from the start of high power ICRF operation on C-Mod
  - Relatively thick B layers built up in most areas (~6 mm)
- Secondary protection tiles (around RF antennas) utilized boron-nitride
- Prior to start of 2005 campaign
  - All PFC surfaces cleaned of B
  - BN replaced with Mo



Significant D Retention with Clean Metal PFCs

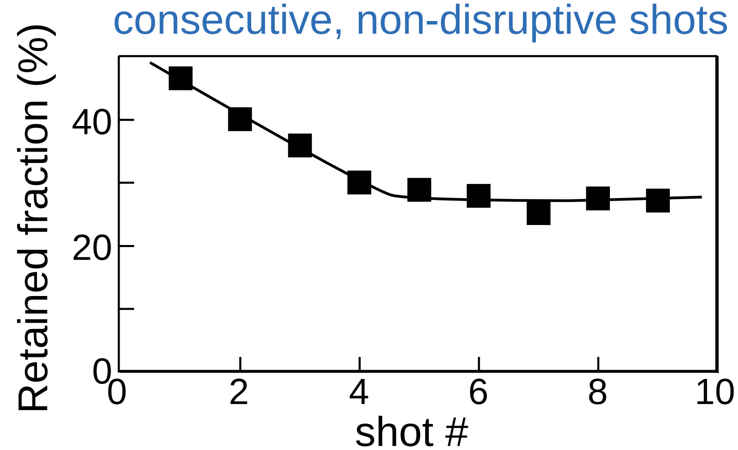
Alcator C-Mod

Retention in C-mod is not caused by co-deposition with boron

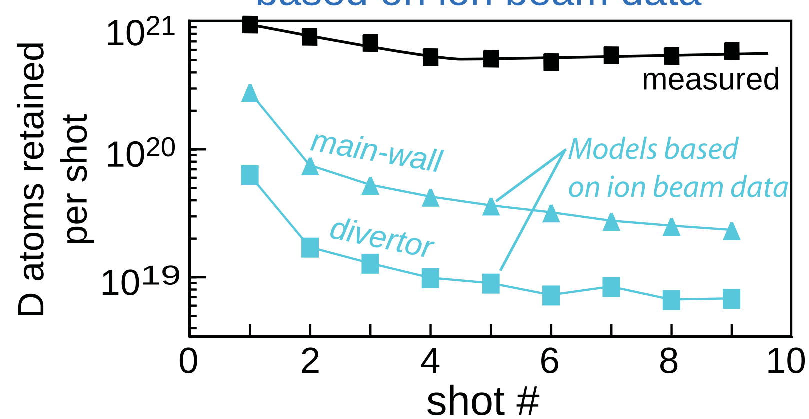


- Similar retention rates observed with all-metal versus boronized PFCs: 20-40% of fuelled gas, ~0.5% of incident ion flux.

No evidence of saturation in consecutive, non-disruptive shots



Retention inconsistent with models based on ion beam data

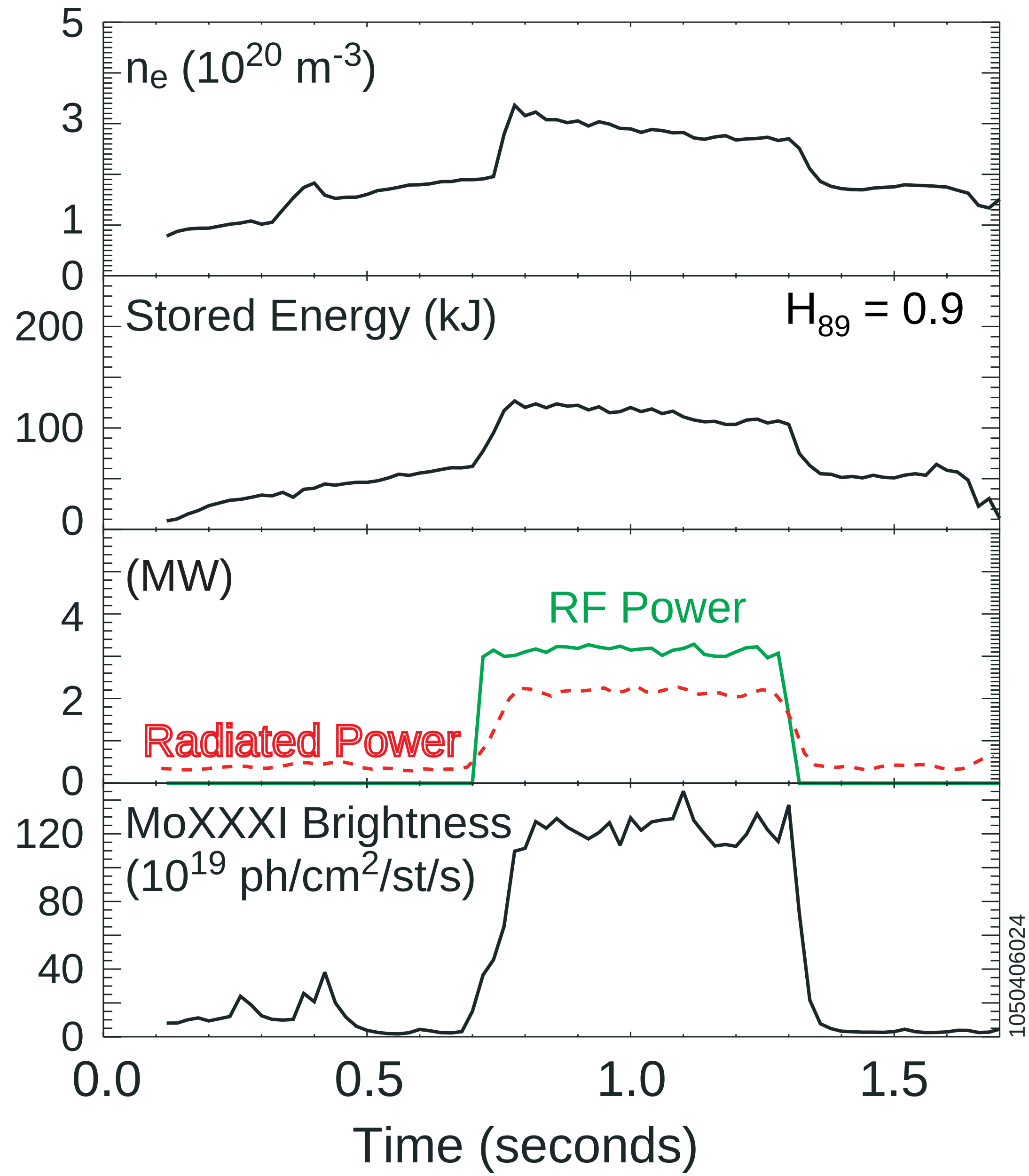


- DIONISOS facility will expose Mo target to high-flux, low-energy D plasma to study retention & saturation.

Whyte, EX/P4-29

Clean Mo PFCs with High Power ICRF Heating Leads to High Core Radiation

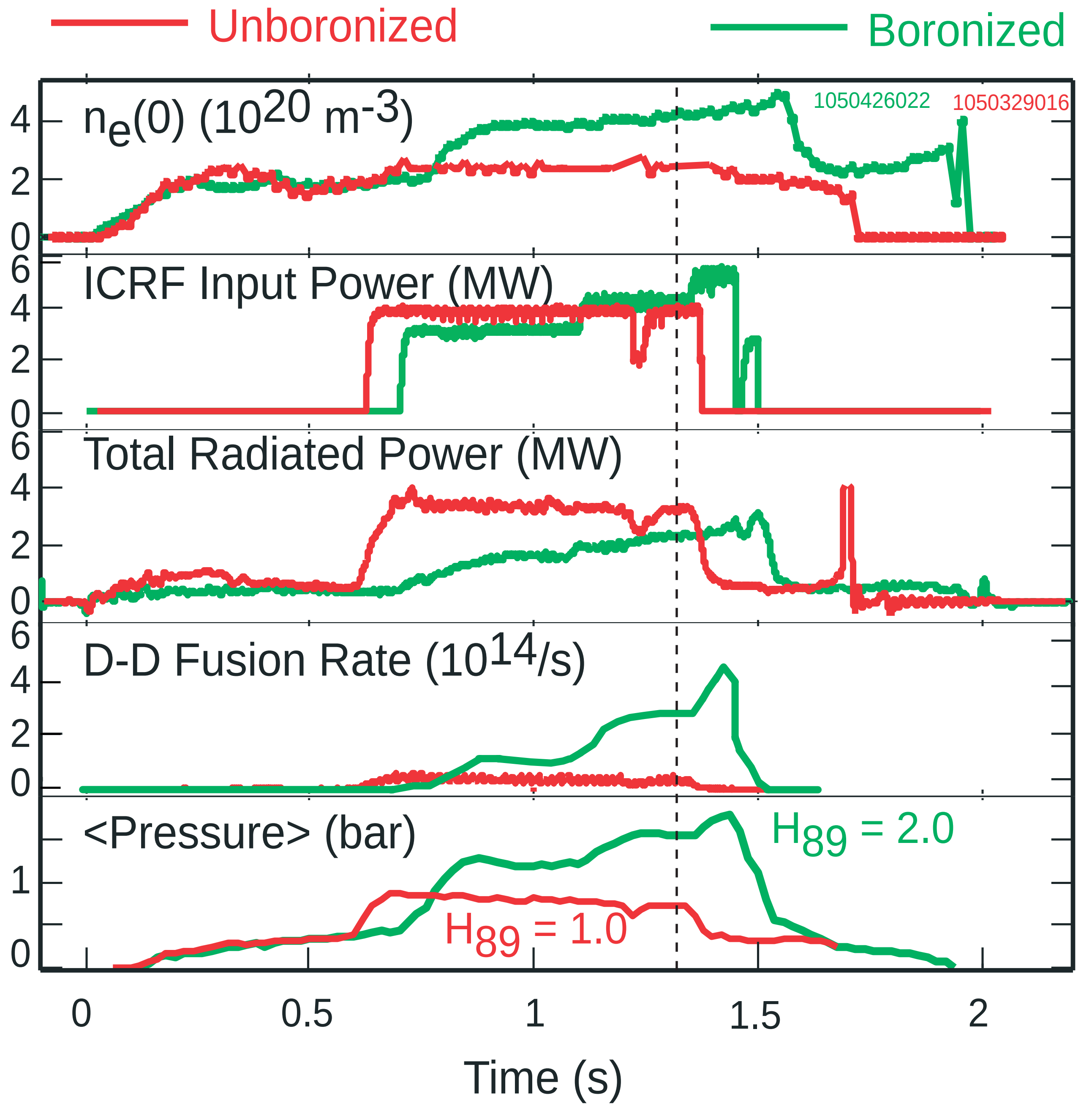
- Unboronized surfaces incompatible with good energy confinement using strong ICRF auxiliary heating (τ_H/τ_{ITER89} < 1.3)
- In all cases Mo radiation from the confined plasma rises rapidly, cooling the plasma
  - Pedestal pressure is suppressed
- Various approaches to improve not effective
  - Increase outer gaps
  - Force divertor detachment
  - Cool SOL with D_2 gas
  - Li pellet wall conditioning
  - Boron dust injection



Boronization Required for High Performance Until Recently, Performed Overnight

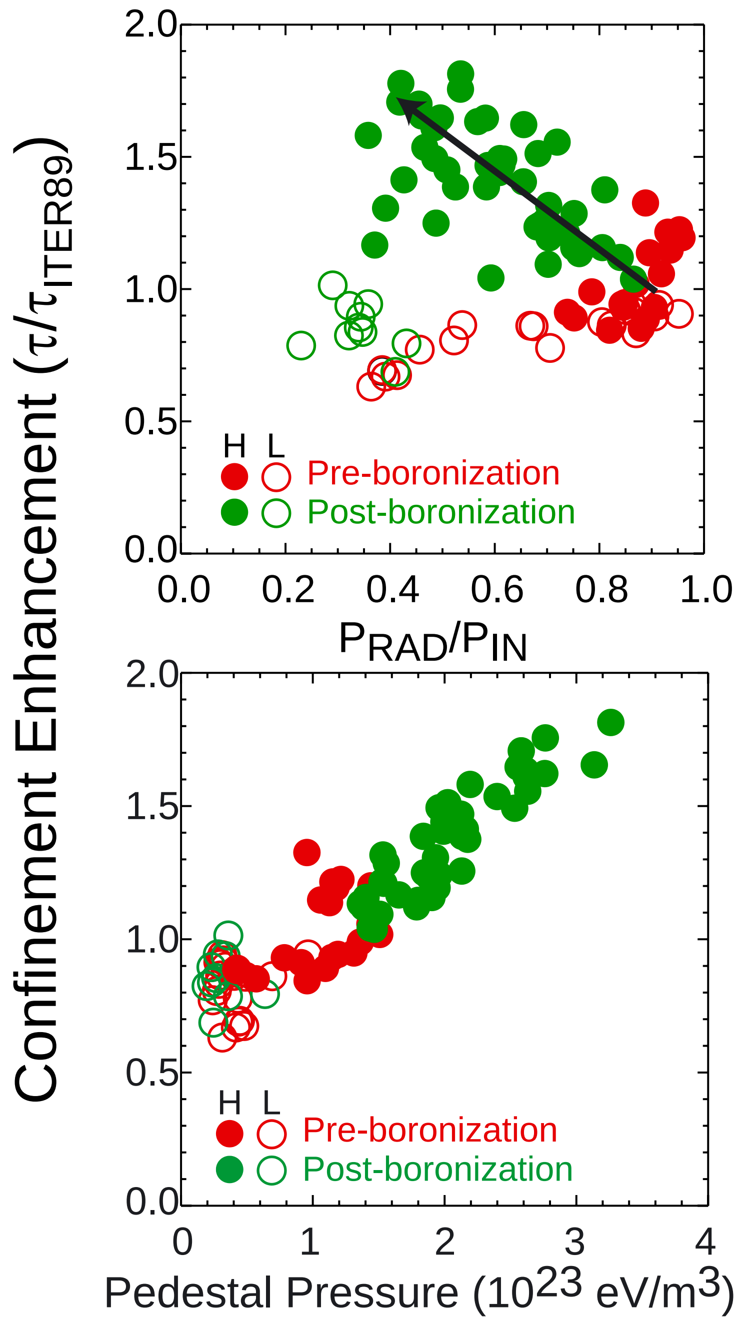
Alcator C-Mod

- After ECD boronization, Mo radiation reduced by factor of 5 or more
  - Fe also reduced
  - B increases
- Energy confinement ~doubles



Monotonic Improvement with Reduced Radiation

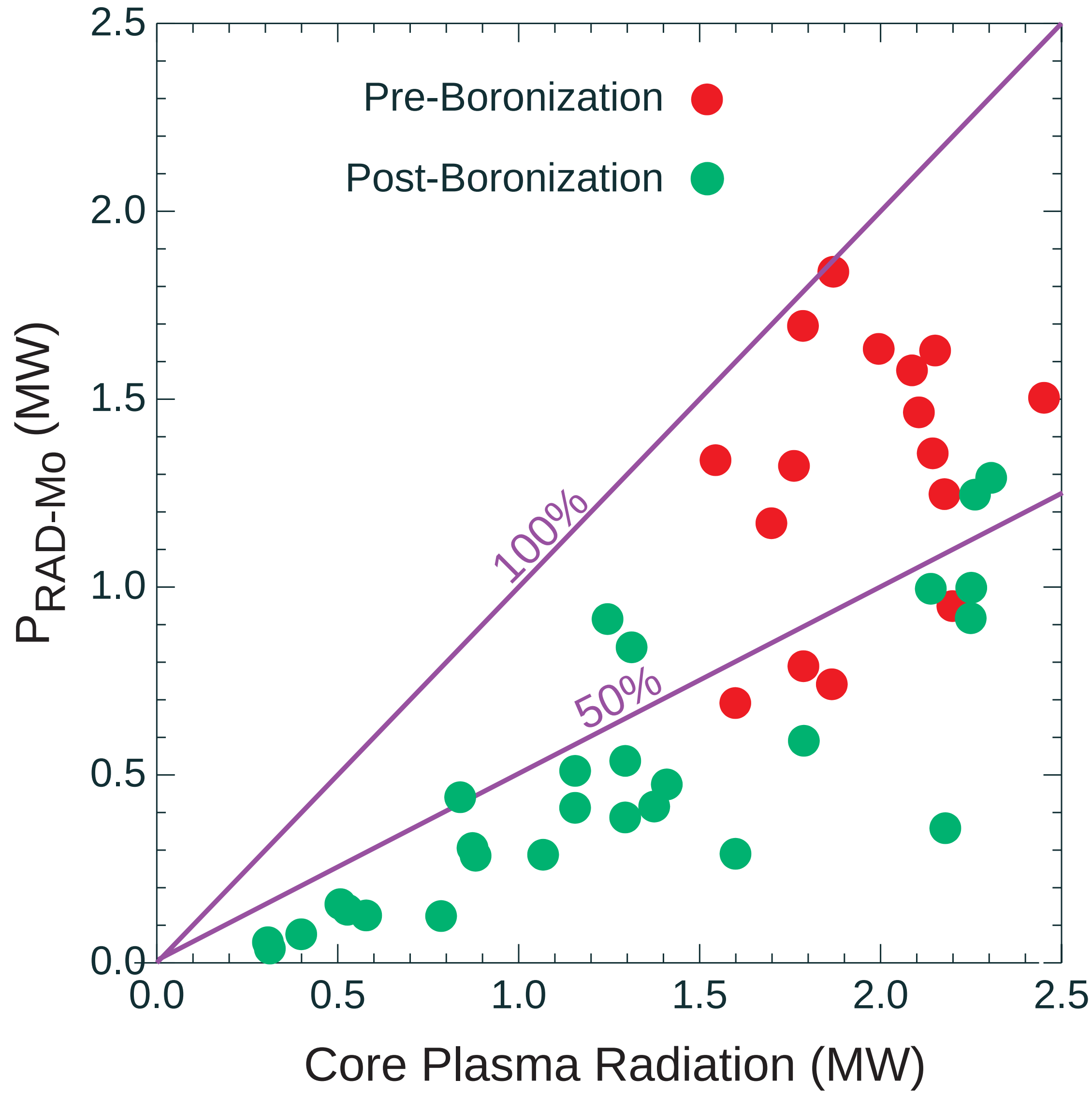
- Radiation cools the pedestal
  - Reduced pedestal pressure
  - Profile stiffness leads to decreased core temperatures and pressures
  - Mo radiates inward of the pedestal, B mostly outside
- After each overnight boronization:
  - Radiation fractions drop
  - Energy confinement in H-Mode improves



Molybdenum is the Primary Radiator Prior to Boronization

Alcator C-Mod

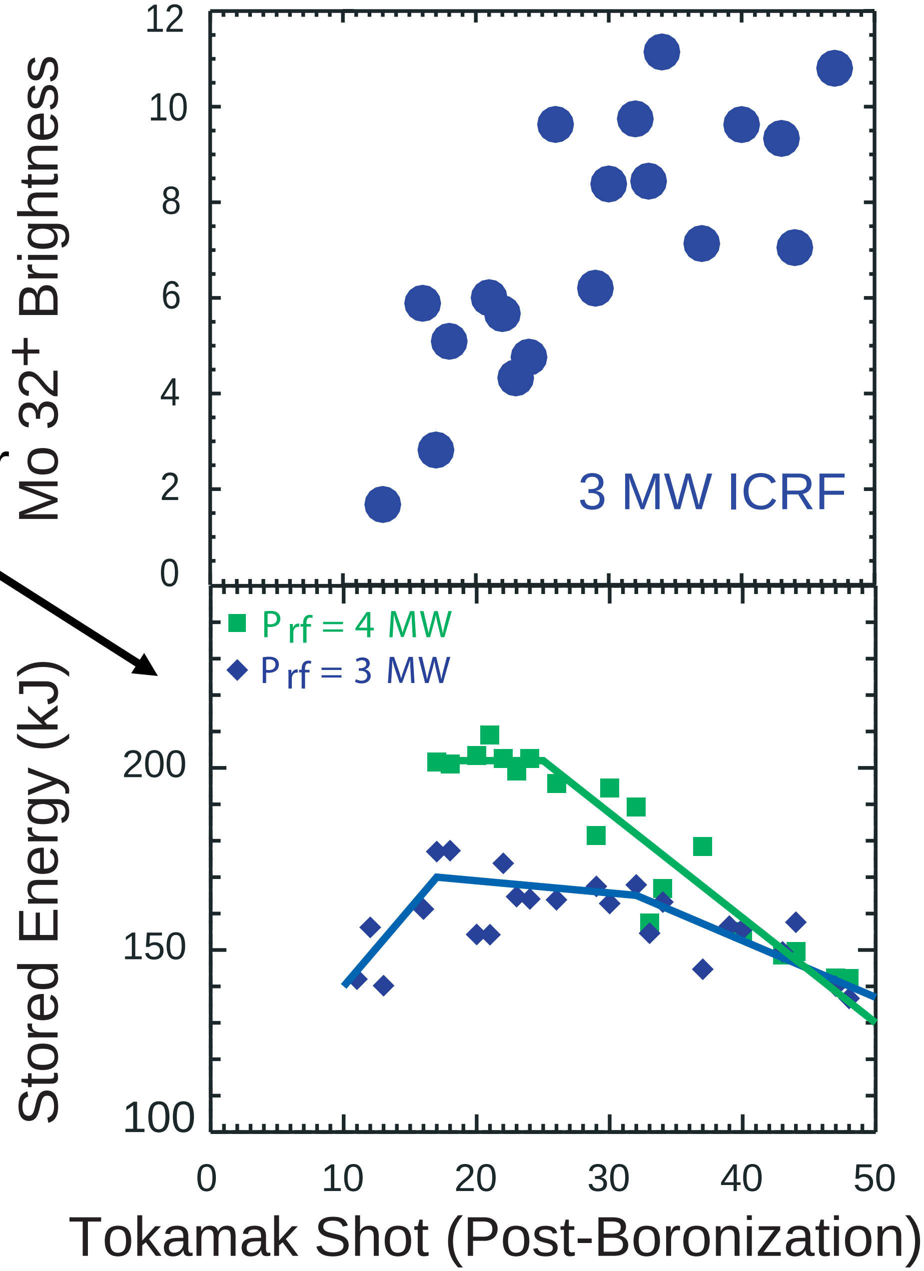
- Prior to boronization
  - Mo accounts for majority of the radiated power
  - Fe accounts for much of the rest (~15%)
- After boronization
  - Mo radiation fraction ¼ to ½ of the reduced total
  - Fe is very small (~4%)
  - B and F account for the rest



Benefits of Overnight Boronization (10 hours) Last 20 to 50 Discharges

Alcator C-Mod

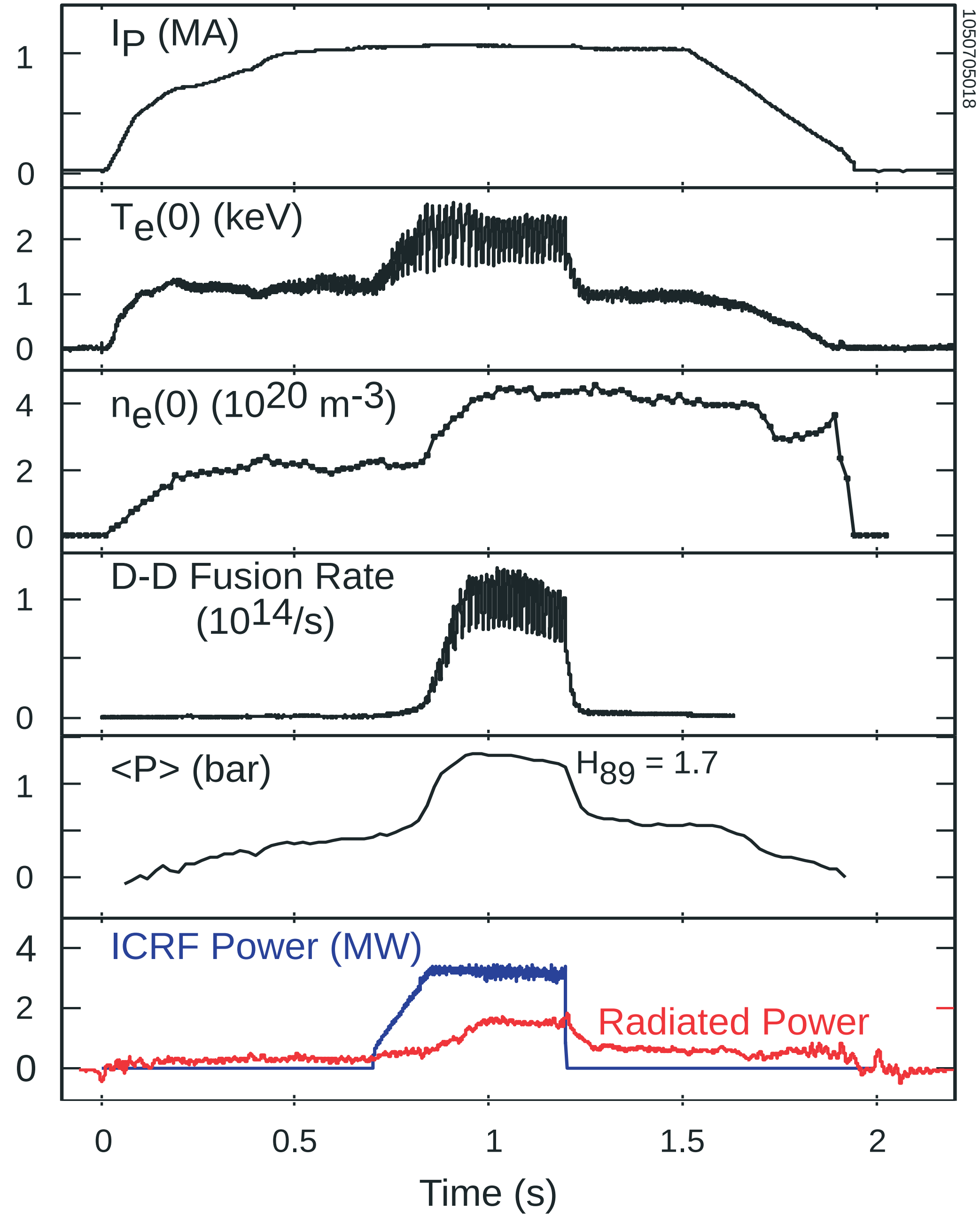
- Following overnight boronization, extended run day to examine evolution with plasma discharges
  - Mo levels rise monotonically from shot to shot
    - Fe does not increase
  - Confinement decrease apparent after ~20 high power discharges (~50 MJ total input energy)
- Post-campaign tile analysis shows thick boron layers on most tiles
  - Exceptions
    - Outer divertor, near usual strike point
    - Top of outboard divertor, especially at leading edges



Inter-Shot Boronization Works Well
Effects Persist for ~ 1 Discharge

Alcator C-Mod

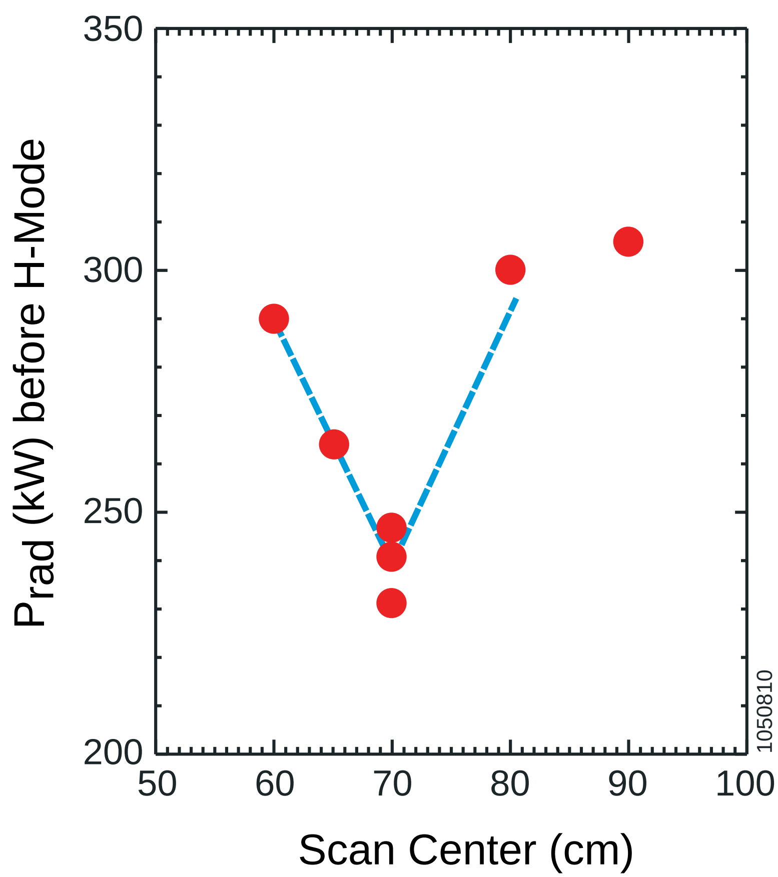
- Close to best performance recovered for discharge following 30 minutes of EC between-shot boronization
  - Localized boron coverage ~100 nano-meter
- Effect wears off after 1 to 2 discharges
  - Opportunity to study and try to optimize parameters



EC Resonance Position Affects Efficacy

Alcator C-Mod

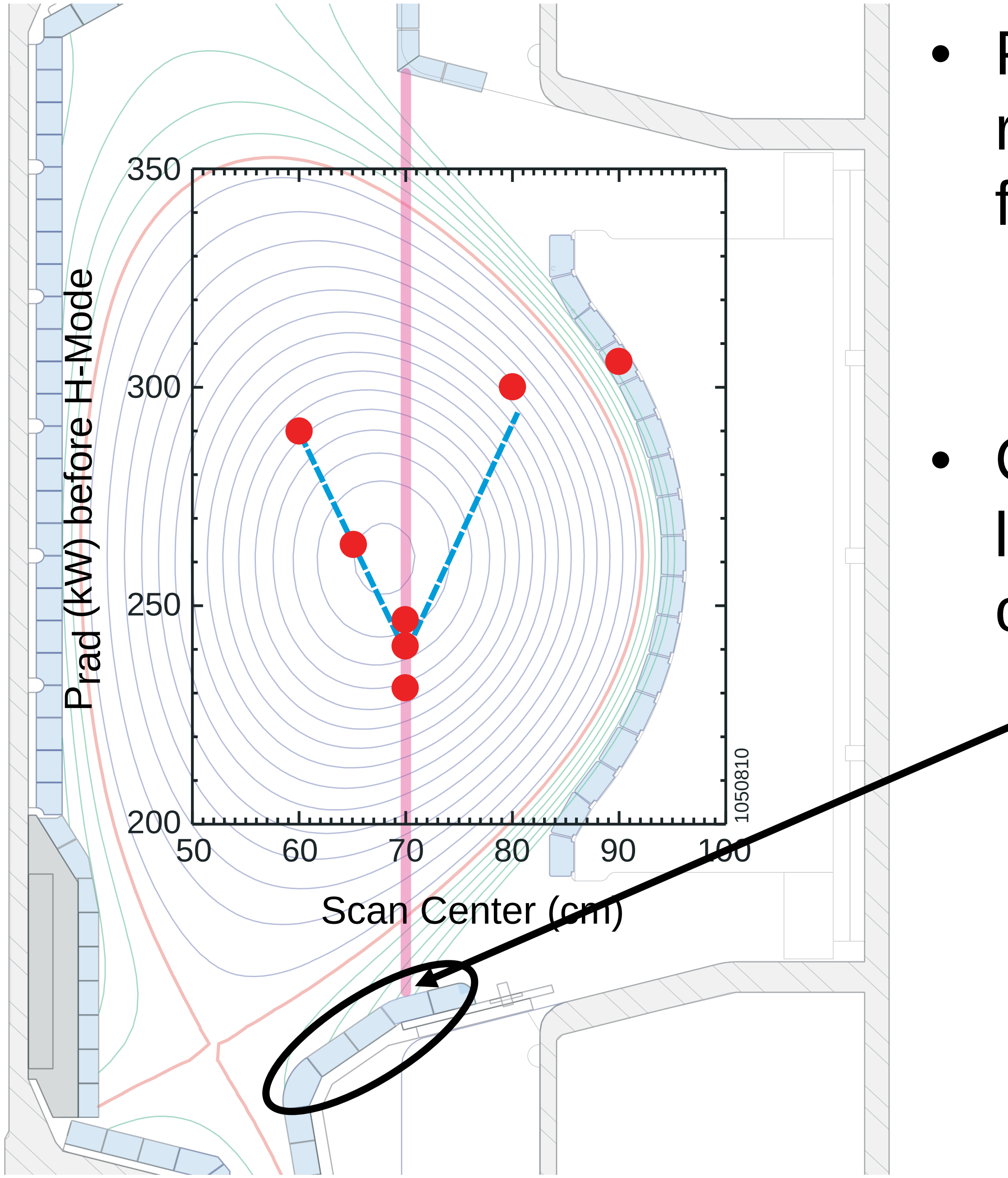
Resonance scanned ±5 cm



- Plasma breakdown at EC resonance (cylinder at fixed R)
  - plasma unconfined to larger R
- Clear result that some locations are better than others

EC Resonance Position Affects Efficacy
Appears to optimize near top of outer divertor

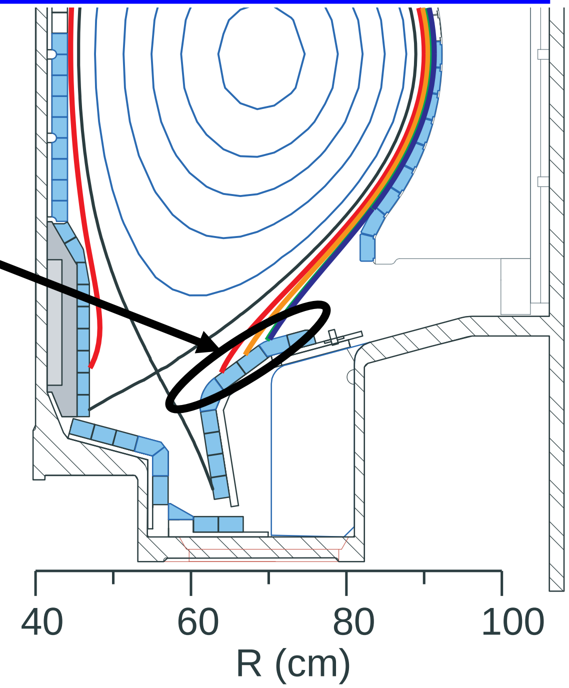
Alcator C-Mod

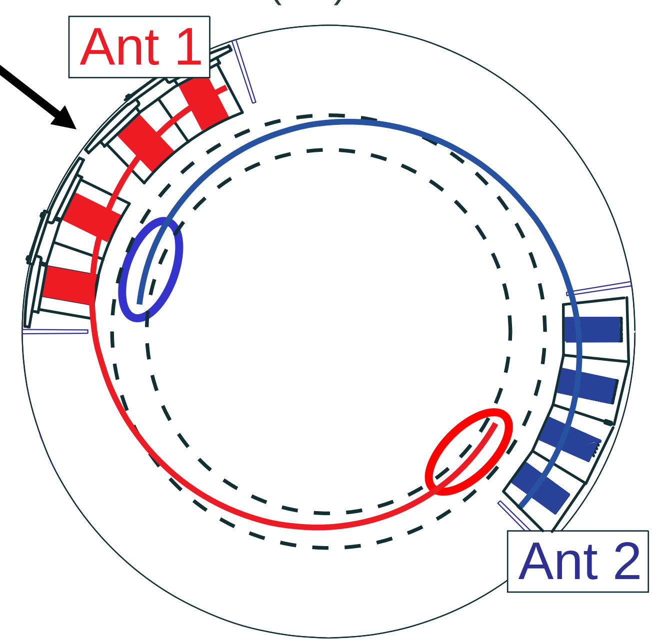


- Plasma breakdown at EC resonance (cylinder at fixed R)
  - plasma unconfined to larger R
- Clear result that some locations are better than others
  - Maps to top of outer divertor
  - Away from highest heat-flux region near strike point

ICRF Sheath Enhancement Responsible for Boron Erosion

- For the equilibrium studied, field lines map from the ICRF antennas to top of outer divertor
- RF sheath-potential enhancement can lead to increased sputtering
- Antennas are on opposite sides of the torus
  - Corresponding field line mapping is to toroidally distinct regions at top of outer divertor
- Conjecture: Boron is preferentially eroded in area with enhanced sheath
  - Supported by energizing different antennas on alternate shots
  - RF erodes boron at least 5 times as fast as ohmic (per joule)
  - Direct sheath potential probe measurements confirm (V_{sheath}>100V) [Wukitch, FT/1-6]





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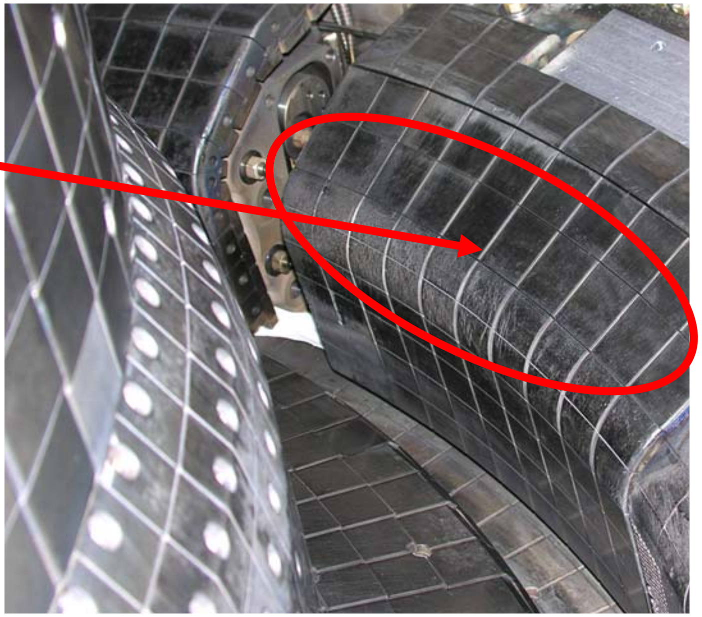

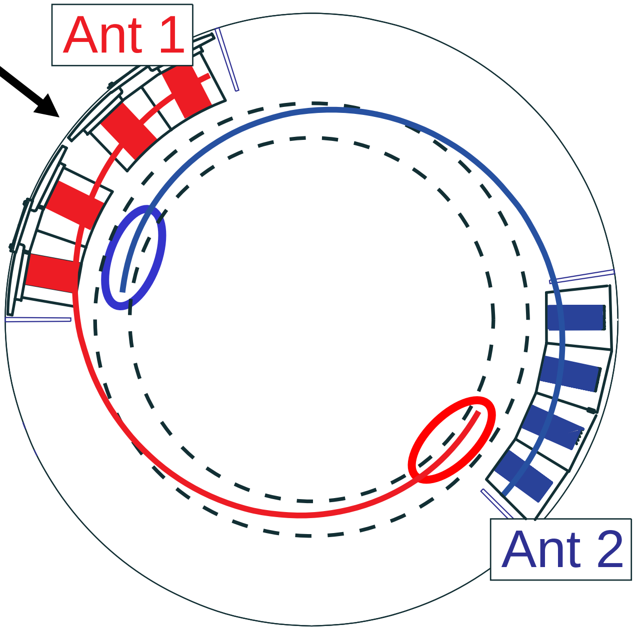

Summary

Alcator C-Mod

- High power heating with high-Z metal PFCs on C-Mod yields high core radiated power and reduced performance
- ECD boronization is very effective in reducing radiation from high-Z impurities (Mo)
  - Leads to dramatic performance improvements
- Between-shot boronization effective (~1 tokamak discharge)
  - Investigation into erosion localization, Mo sources
    - High heat-flux region of the divertor, near strike points, is not the critical source region for Mo which reaches the core plasma
    - ICRF sheath enhancement (>100 V) at top of outboard divertor implicated
- Possible implications for ITER
  - Tritium retention in high-Z PFCs?
  - Compatibility of tungsten?
  - Wall-coating/conditioning for long-pulse?