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

- 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

- 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?

- 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

• 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*

*ASDEX-Upgrade using W-coated graphite [Dux, previous talk]
JET planning to use W
Boronization used Routinely for Wall Conditioning

• 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\textsubscript{resonance} = 0.088 tesla)
  – \( T_e \sim 10 \text{ eV}, \ T_i < 1 \text{ eV}, \ n_e \sim 10^{16} \text{ m}^{-3} \)
  – Cleaning using deuterium
  – Boronization using 10% \( \text{B}_2\text{D}_6 \) / 90% He
• \(~10\)-hour boronization
  – average coverage of 200 nanometer
Boronization used Routinely for Wall Conditioning

- 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

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.

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

No evidence of saturation in consecutive, non-disruptive shots

Retention inconsistent with models based on ion beam data

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 ($\tau_H/\tau_{\text{ITER89}} < 1.3$)
- 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

- 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

- 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

• 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

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

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

- 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 ($V_{\text{sheath}} > 100V$) [Wukitch, FT/1-6]
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Summary

- 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?