Between-Shot Boronization

• Boronization techniques on C-Mod
• Effects of overnight boronization
• Persistence
• Between-shot Electron-Cyclotron Discharge boronization
• Sensitivity to EC resonance position
• Comparisons with conventional glow boronization

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Boronization used routinely for wall conditioning

• C-Mod utilizes all-metal plasma facing components (molybdenum)
• Primary wall conditioning regimen following vacuum breaks
  – Bake (120 C), Discharge Clean, Operate, Boronize
• Discharge cleaning and boronization accomplished using Electron Cyclotron Resonance low temperature plasma (ECDC)
• ECDC parameters:
  – 2.5 kW, 2.45 GHz RF
  – Use toroidal field only; scan to move resonance from inner wall to beyond outer limiters
  – $T_e \sim 10$ eV, $T_i < 1$ eV, $n_e \sim 10^{16}$ m$^{-3}$
  – Cleaning using deuterium
  – Boronization using 90%He/10%B$_2$D$_6$
• ~10-hour boronization (overnight), average coverage of 200 nano-meter
Boronization required for high performance
Until now, performed overnight

- Prior to boronization, H-mode performance degraded
  - Impurity radiation usually dominated by Mo
- After boronization, Mo radiation reduced by factor 5 or more
  - Fe also reduced
  - B increases
Benefits of overnight boronization (10 hours)  
last 20 to 100 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 shelf, outboard of lower divertor
Inter-shot boronization works well
Effects persist for ~ 1 discharge

- Close to best performance recovered for discharge following 30 minutes of EC boronization
  - Average boron coverage ~10 nanometer
- Effect wears off after 1 to 2 discharges
  - Opportunity to study and try to optimize parameters
Benefits Increase Monotonically with Time of Between-Shot Application

- **R = .44-.8 m, dwell .52 m**
  - Inner wall and divertor
- **R = .5-1.03 m, dwell .52 m**
  - Divertor and outboard

**Total neutrons (10^{13}) (0.7 < t < 1.2 sec)**

- **Unboronized**

**Length of boronization prior to shot (minutes)**

- **0.0-10**
- **10-20**
- **20-30**
- **30-40**
EC Resonance Position Affects Efficacy

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

Resonance scanned ±5 cm

![Graph showing the relationship between scan center (cm) and rad (kW) before H-Mode.](image)

- The graph indicates a peak in rad (kW) before H-Mode at around 70 cm, with a drop and then a rise as the scan center moves away from 70 cm.
EC Resonance Position Affects Efficacy
Appears to optimize near top of outer divertor shelf

• Plasma breakdown at EC resonance (cylinder at fixed R)
  – but unconfined to larger R
• Clear result that some locations are better than others
Conventional Glow Discharge Boronization
NOT Effective

- Direct comparison of glow boronization with ECDC boronization (20 minutes in all cases)
  - Same target tokamak plasma parameters
- Glow ineffective
  - Does not reduce radiated power
  - Little difference from unboronized
Summary

- ECDC boronization is effective in reducing radiation from high Z impurities (Mo)
  - Leads to dramatic performance improvements
- Between-shot boronization (2 to 10 nm coverage) effective (~1 tokamak discharge)
  - Investigation into localization becomes practical
    - Initial indication that divertor near strike points is not the critical region for Mo influx
- Glow boronization ineffective (so-far) in C-Mod
- Future studies aimed at pinning down localization issue more precisely
  - Develop technique(s) that can work during the tokamak pulse (required for steady-state)