Operation of Alcator C-Mod with high-Z plasma facing components and implications

Motivation
Pre-boronization
Effect of boronization
Role of impurities
Recycling
Implications for ITER and beyond
Summary

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Operation of a reactor with carbon Plasma Facing Components (PFCs) has obvious disadvantages

- Simple estimates of reactor erosion rate outside the divertor (‘main chamber’) includes:
  - Charge exchange neutrals
  - Ion fluxes
  - \( \rightarrow \) High-Z PFCs have much lower erosion rates - longer wall lifetime

- ELMs which cause localized, high rates of erosion, are not included

- Divertor erosion/redeposition rates potentially much higher

- Neutron irradiation of carbon leads to:
  - Thermal conductivity drop (2 - 10)
  - Material ‘swelling’ (growth in volume)

- Multiple studies of such materials issues have led reactor designers to choose tungsten
Use of carbon in ITER raises another issue - tritium retention

Background

- Estimates of T retention in ITER are high
  - T retention in JET and TFTR ‘before cleaning’ ~ 30% of that injected (15% after ‘cleaning’).
  - Simple extrapolation to ITER implies not many discharges before stopping to remove the T

- Tritium removal techniques are in their infancy
  - Assuming ITER has overnight or a weekend to remove the T requires much higher T removal rates than have been demonstrated on a large scale

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TFTR experience</th>
<th>JET experience</th>
<th>ITER requirement</th>
</tr>
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<tbody>
<tr>
<td>Time devoted to T removal</td>
<td>1.5 months</td>
<td>3 months</td>
<td>5-14 hours</td>
</tr>
<tr>
<td>Fraction of T removed</td>
<td>50%</td>
<td>50%</td>
<td>~100%</td>
</tr>
<tr>
<td>Tritium removal rate</td>
<td>~ .0014 g/hr</td>
<td>~ .0028 g/hr</td>
<td>~25-70 g/hr</td>
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Factor of $10^4$ increase needed
How do we determine whether tungsten will work in a reactor (or ITER)?

- Tungsten has obvious advantages over carbon
  - Very low erosion rate
  - Reasonable resistance to neutron damage
  - Low tritium retention
    - W (.1-1% T/W), C (40-100% T/C)

- Use of tungsten carries risks
  - Melted locations can lead to enhanced heat loads and further melting
  - Allowable W concentration in the plasma is very low (~10^-4 - 10^-5)

- We need operational experience to determine
  - Whether the advantages of tungsten are real
  - Whether there may be unforeseen problems

- Based on the above, ITER has relegated carbon to a small fraction of PFC surfaces. The community is pursuing T removal techniques.
- At some point during ITER operation, it should provide the high-power, long-pulse experience with fully high-Z PFC surfaces needed for a reactor (DEMO)
Current PFC surface coating techniques are probably not reactor-relevant either either

- Essentially all tokamaks coat their surfaces with a thin coating (fractions of a micron) of a low-Z material
  - Boron (‘boronization’) for most tokamaks
  - Be (‘berylliumization’) for JET
- Such layers ‘help’ operation and performance
  - Lower impurity levels, can make discharge breakdown more reliable

**BUT**

- At best, we only have a qualitative understanding of the effects
- Current coating techniques are inherently non steady-state
- **ITER’s confinement & operation is based on present experiments that utilize surface coatings**

If coatings cannot be used in ITER (reactor) will the performance be as predicted?
C-Mod is ideal for addressing the issues of high-Z PFC surfaces, and the role of low-Z coatings

- First wall material
  - Molybdenum - close to tungsten in terms of erosion, D retention, thermal conductivity, melting temperature
  - Mo radiation at C-Mod core $T_e$ close approximation of tungsten at ITER core $T_e$

- Shape - The ITER divertor was based on C-Mod results with the vertical plate

- Plasma characteristics similar to ITER
  - Divertor:
    - Density, temperatures
    - parallel heat flux (0.5 GW/m²),
  - SOL: opaque to neutrals

- Boron layers can be removed easily to compare uncoated to coated operation

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C-Mod campaign dedicated to the comparison of un-boronized and boronized high-Z operation

- Before cleaning tiles
  - The majority of Mo tiles were covered with thick B layers (~6µm thick)
    - (note: such thick, widespread, layers are also common in carbon PFC tokamaks)
- All surfaces cleaned of accumulated boron
  - Surface analysis showed B/(Mo+B) dropping from 99% to 10-20%*
    - B likely ‘trapped’ in the topography of the surface
- All BN tiles replaced with molybdenum
- Long operational period before boronization to properly characterize un-boronized PFC operation.

*See Wright poster KP1.0064, Wednesday, 9:30 AM, Whyte Oral RO3.00006 Thursday 2:00PM
Un-boronized surfaces generally had poor plasma performance

- Considerable time spent core molybdenum level without boron-coated PFCs
  - Changing plasma-PFC gaps
  - Forcing detachment of the divertor
    - Lowered Mo sources there but no effect on the core Mo levels
  - Cool the edge plasma (SOL) with gas
    - Lowered Mo sources, $n_{Mo}/n_e$, but energy confinement still poor
  - Lithium pellets - no effect
  - Finally, we added boron dust to the plasma
    - raised $n_B/n_e$ to boronized levels
    - no effect on energy confinement

- In all cases the radiation rose rapidly, cooling the plasma
- Un-boronized surfaces were not effective in achieving good energy confinement with auxiliary heating ($H_{ITER,89} < 1.3$)
H-mode very different pre- and post-boronization

- Comparison of two discharges
  - Pre-boronization
  - Post-2nd-boronization
- Pre-boronization
  - $\bar{n}_e$ & impurity radiation rapidly rise at start of H-mode
  - Stored energy and energy confinement low ($H_{\text{ITER,89}} < 1.3$)
- Post-1st boronization
  - $\bar{n}_e$ and radiation rise more slowly (smaller impurity influx)
  - Energy confinement much better
- Post-2nd boronization
  - Impurity levels further reduced
  - World record tokamak volume-averaged plasma pressure of 1.8 atmospheres
    - at the ITER $\beta_N$ & $B_T$ ($H_{\text{ITER,89}} \sim 1.8$)
Boronization greatly enhanced energy confinement

- After each boronization
  - Radiation fraction dropped
  - Energy confinement improved

- Consistent H-mode data
  - Higher radiated fraction - lower energy confinement

See Hutchinson oral RO3.00003 Thursday 2:00PM
Profile stiffness and pedestal cooling explain the energy confinement degradation at high $P_{\text{RAD}}/P_{\text{IN}}$.

- Radiation losses lead to a cooler pedestal
- Profile stiffness causes $T_e$ and $P_e$ to decrease across the entire profile
  - Lower stored energy and H-factor
- Reducing Mo (replaced w/B) leads to hotter pedestal and higher H-factor
  - Molybdenum (Z=42) radiation efficiency in the pedestal is much higher than that of boron (Z=5)
Molybdenum and iron radiation are strongly affected by boronization

- Molybdenum is the primary radiator before boronization
- Fe and Mo fractions approaching 0.1%*
  - Fe from stainless steel components
- First boronization
  - Large drop in molybdenum & iron
  - Layer wore off very fast
- Second boronization
  - Molybdenum levels drop further
- Molybdenum radiation rises after each boronization (consistent with eroding boron coating of PFCs)
- Iron radiation stays low after first boronization
  - Coating of support structures (vessel)

*See Reinke poster KP1.0009, Wednesday, 9:30 AM
Molybdenum is the primary radiator before boronization

- **Prior to boronization**
  - Molybdenum radiation* accounts for most of the radiated power, $P_{RAD}$
  - Iron radiation* accounts for $\sim 0.15x P_{RAD}$
- **After boronization**
  - Molybdenum radiation 0.25-0.5x $P_{RAD}$
  - Iron radiation $\sim 0.04x P_{RAD}$

*See Reinke poster KP1.0009, Wednesday, 9:30 AM
Boron and fluorine complete the radiated power accounting

- Boron and fluorine radiation account for the remainder of $P_{\text{RAD}}$
  - $n_B/n_e$ increases x5-10 after boronization ($n_B/n_e = 1-2\%$)
  - $n_F/n_e$ stays constant or increases across boronization ($n_F/n_e = 0.2\%$)
  - $F$ appearing as a gas
  - $P_{\text{RAD,B}} + P_{\text{RAD,F}} \sim 500\text{kW}$ based on spectroscopy & transport simulations

- Radiated power accounting reasonably good
Boronization has a short-term effect on recycling

After an overnight boronization
- Amount injected to achieve the desired density very small
- Walls are fueling (R > 1)
- Gas seems to be coming from PFC surfaces near the midplane
- The recycling effects are mostly worn off after 50 shots
  - PFC surfaces shift from dominant fueling to almost pumping
- Long after boronization PFC surfaces pump (described on next slide)
The PFC surfaces can retain large amounts of D

Pre-boronization
- D retention in PFC surfaces larger than expected
  - Amount retained can approach 50% of that injected for the discharge

Post-boronization
- PFC surfaces fuel the plasma immediately after boronization
- Eventually (~ 100 discharges), PFC surfaces D retention similar to pre-boronization
  - D retention process uncertain; not expected for Mo; surface impurities?
- Time-integrated D retention is much smaller*
  - Disruptions, planned or unplanned, remove most of the retained D

*See Wright poster KP1.0064, Wednesday, 9:30 AM, Whyte Oral RO3.0006 Thursday 2:00PM
Between-discharge boronization: a tool for finding impurity sources & optimizing operation

- Initial development of between-discharge boronization*
  - Maintain constant conditions
  - Determine the most important molybdenum source location

- Scanned the boronization discharge resonance across the chamber
  - Most effective in reducing radiation in the following discharge @R=70
  - Effect lasts 1 discharge consistent w/overnight boronization

- More experiments planned
  - Better locate Mo sources
  - Optimize speed and effectiveness
  - ‘surgically’ apply boron layer where needed

*See Marmar oral RO3.00004 Thursday 2:00PM
Several results point towards important Mo source locations outside the divertor high heat flux region

- Between-discharge boronization
  - Best results imply points R≥65 are important
- Divertor detachment
  - Reduced measured Mo source rate at strike points
  - Core Mo levels unaffected
- Scaling studies [NF 41 (2001) 585] show
  - Outboard impurity sources have 100x higher probability of reaching the core plasma
  - RF sheath rectification enhances ion impact energies (sputtering) outside the divertor
Boronization coatings (gain or loss) lead to dramatic effects in a high-Z tokamak

- Comparison of boronization on carbon and molybdenum PFC tokamaks shows similarities and differences

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<thead>
<tr>
<th></th>
<th>Carbon PFCs</th>
<th>Molybdenum PFCs</th>
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</thead>
<tbody>
<tr>
<td>Boronization effect</td>
<td>Lowers O, Fe, Ni, C, Increases B</td>
<td>Lowers Fe, Mo (O already low), Increases B</td>
</tr>
<tr>
<td></td>
<td>Lowers recycling coef. (R&lt;1)</td>
<td>Increases recycling coef. (R&gt;1)</td>
</tr>
<tr>
<td>Impurity reduction time scales</td>
<td>10s of shots for C, Longer for Fe, Ni</td>
<td>10s of shots for Mo, Longer for Fe</td>
</tr>
<tr>
<td>Effect of the layer wearing off</td>
<td>Small - B replaced by C, radiation low &amp; outside the pedestal - energy confinement still high.</td>
<td>LARGE - B replaced by Mo, radiation increases strongly, energy confinement degrades</td>
</tr>
</tbody>
</table>

- Based on operational experience and visual inspection during a vent - most surfaces (Fe and most PFCs) have coatings that are never eroded
Implications for ITER and reactors

- ITER or reactor with all tungsten Plasma Facing Components
  - ITER edge plasma (SOL) opacity to impurities should be similar to C-Mod
  - Large ELMs lead to impurity sources that C-Mod does not have
  - The extrapolation of the impurity source process to a reactor is uncertain, but still

→ High-Z first wall is a significant concern for affecting the core plasma
  - Current boronization techniques unlikely to be applicable
  - More work needed
    - Further understanding of the sources and scaling
    - New, more ITER relevant wall coating techniques (localized, during a discharge)

- ITER current plan is for Be (main chamber surfaces), W (divertor), C (strike point area)
  - Will the C and Be erode and coat important tungsten impurity source locations?
  - Is the combination of tungsten’s good thermo-mechanical and tritium-retention properties with a coating what we want?
Summary - ‘C-Mod boron coating studies expose issues for reactors’

- Boronization leads to low radiation and good energy confinement

- The D retention in molybdenum surfaces is higher than expected
  - May be due to surface impurities
  - Long term retention ‘naturally’ reduced under continued operation
  - Not clear of processes that are involved and how they extrapolate to long-pulse

- High-Z surface boronization parallels some effects found in carbon PFC tokamaks
  - Most vessel and PFC surfaces need one coating (slow erosion)
  - The B coating in localized regions erodes more quickly (10s of shots)
  - The underlying material (C or Mo) quickly returns to the surface and plasma
    - For carbon PFC tokamak - no big deal, carbon radiation only partially cools the pedestal and energy confinement still good
    - NOT TRUE for high-Z, radiation losses too high, degraded confinement

- Between-discharge boronization being developed for operation and research tool
It is important to pay attention to PFC issues

- We already have concerns about using carbon PFCs in a reactor
- C-Mod experience raises concerns regarding tungsten as well

- The PFC material is central to the success of a fusion reactor or ITER
  - Better understanding of boronization and its erosion needed
  - More investigation of material properties (carbon and high-Z) needed

- We should not ignore the long-term questions of use of tungsten or carbon in a reactor.