Plasma-surface interactions, SOL and divertor physics: Implications for ITER

Transport
ELMs & disruptions
D/T retention & removal
Materials
Summary

Bruce Lipschultz
For the
ITPA SOL/divertor committee
It is a challenge to use our current experience to predict ITER performance

<table>
<thead>
<tr>
<th>Current tokamaks</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational experience primarily carbon Plasma Facing Components (PFCs)</td>
<td>Primarily Be with lesser amounts of carbon and tungsten</td>
</tr>
<tr>
<td>Surfaces coated with low-Z (e.g. boronization)</td>
<td>No boronization planned (but Be may serve that purpose)</td>
</tr>
<tr>
<td>D/T retention ~ 3-30% of injected gas</td>
<td>T retention should be ~ 0.1% to Maximize operational availability</td>
</tr>
<tr>
<td>Low ELM/disruption transient loadings</td>
<td>High transient heat loads - limits PFC lifetime</td>
</tr>
</tbody>
</table>
We are building a basic understanding of radial transport in the SOL

- $\lambda_Q = 2\lambda_T / 7 \Rightarrow$ ITER parallel power flow width similar (normalized to R) to current tokamaks. $Q_{\|} \sim P/(2\pi R\lambda_Q)$ NOT $P/R$

- Pressure gradients just outside the separatrix are well-organized by Electromagnetic Fluid Drift Turbulence models $\Rightarrow$ direct connection between gradients and underlying turbulence.

- Potential to predict plasma profiles from first principles.

LaBombard, Nucl. Fusion 45 (2005) 1658

Much better understanding of flows in the edge

SOL flows control impurity transport in the SOL as well as tritium co-deposition

- Standard models can’t match measured flows
- New inner wall probe measurements provide clues:
  - High-field SOL: lower pressure than low-field SOL
  - Pressure imbalance => driving parallel flows and M~1 flows at high field side
  - Pressure imbalance driven by low-field side ballooning transport out of core, across separatrix
- Evidence of transport-driven flows setting toroidal rotation boundary condition for confined plasma

Allows better understanding of impurity migration and T retention
ELM filaments travel far through the SOL to the wall

- General experience => Type I ELMs reduce ITER divertor plate lifetime
- We are also concerned about ELM loading of the main chamber PFCs

- Filamentary nature of ELMs (n ~ 7-15) rotating toroidally and poloidally

- ELMs travel far into the SOL having a substantial effect on the density and temperature at the limiter

↑ Loarte et al, Paper IT/P1-14
Type 1 ELM filaments lead to local hot spots on limiters

- Visible image of ASDEX-Upgrade limiter*

Type 1 ELM filaments lead to local hot spots on limiters

• Individual ELM filaments lead to hot spots on limiter surface*

Type 1 ELM filaments lead to local hot spots on limiters

*Individual ELM filaments lead to hot spots on limiter surface*

*Herrmann et al J. Nucl. Mater. 337-339 (2005) 697*
Type 1 ELM filaments lead to local hot spots on limiters

- Individual ELM filaments lead to hot spots on limiter surface*

Heat loads are less localized when averaged over ELMs

- When averaged over ELMs the heat load is more uniform*

- ~10% of ELM energy goes to non-divertor surfaces
- $T_i$ in ELM representative of pedestal $\Rightarrow$ sputtering
- Concerns for ITER Be limiter and upper divertor**
- Divertor heat flux footprint similar to between ELMs

- A number of opportunities are being pursued to reduce concerns over ELMs
  - Small ELMs **, pellet pacing, external coils....

**Loarte et al, Paper IT/P1-14

Disruption statistics reveal details of energy balance during a disruption

• A significant fraction of the stored energy is often lost before the thermal quench
  • Energy lost through L-H transitions.....
• => specify fewer ITER high power disruptions
• ITB and VDE disruptions are the most dangerous: All the stored energy comes out rapidly

• The divertor receives less of the thermal energy as the stored energy increases
• Energy going to main chamber surfaces
Tritium retention is a central emphasis of SOL/divertor work

- Estimates of T retention in ITER are uncertain
  - All carbon PFC tokamaks have D retention per discharge ~3-50% of that injected
  - ITER will have much less carbon
  - Be does co-deposit with tritium
  - Be will not migrate to remote cooled locations as easily as carbon => less likely to accumulate thick co-deposited layers
  - Be releases T at lower temperatures than carbon as well.

=> Modelling estimates give a range of 1-3 weeks operation before T site limit reached
T retention on tile sides will be more important in ITER

- 20% of the total D retention is on the sides of tiles
- Co-deposition with C ions and molecules
- ITER design increases the ratio of tile side to front surface areas ~x4 over current carbon PFC tokamaks

Cross-tokamak studies indicate tile side D retention
- $\propto$ surface ion fluence (largest in high fluence areas)
- Lowest in fully high-Z tokamak
- Reduced by elevated tile temperatures
Studies have revealed another process besides co-deposition that leads to T retention

- A number of tokamaks have reported that co-deposition cannot explain the level of D retention measured (e.g. Tore Supra, C-Mod, JT-60U)
- New laboratory studies have found that D can be stored deep below surface
  - True for carbon AND molybdenum

- Deep retention in tiles will add to ITER T retention levels
  - Potentially dominate over co-deposition in high flux regions
  - Potentially more difficult to remove through surface T removal techniques
  - Area of increasing emphasis for ITPA
Mixed materials in ITER are a mixed blessing

• A number of alloys form
  ■ Beryllides (e.g. Be$_2$W) lowers tungsten melting temperature
  ■ Carbides increase T retention (WC) and lower T retention (BeC)
  ■ Alloys could form barriers to the out-diffusion of T

• Chemical sputtering should be reduced in ITER
  ■ Be or W on carbon reduces carbon chemical sputtering
  ■ Carbon is a small fraction of PFCs

• Carbon tiles could even be doped with metals before installation such that the chemical erosion is reduced
Many tritium removal techniques are being developed

• Tritium removal techniques include
  ■ Heating the surface to increase T diffusion
    ○ e.g. laser, disruptions
  ■ Chemical removal of carbon (and T)
    ○ Oxygen exposure, discharge cleaning…
  ■ Ablation of the carbon - freeing the T
    ○ e.g. flash-lamps, lasers

• All techniques must be
  ■ Compatible with ITER toroidal field
  ■ Not cause dust
  ■ Able to remove T from mixed material surfaces
    ○ Be, W, C, BeC, WC, Be₂W
  ■ Not cause problems for subsequent operation
    ○ Impurities or damage to vessel

• A figure maybe?
High-Z operational experience still not encouraging enough for ITER to go all high-Z

- ASDEX-Upgrade (85% W-coated carbon)
- C-Mod (100% solid Mo tiles)

- Both tokamaks report
  - Core high-Z content rises quickly after boronization
    - Similar to C after boronization
  - ICRF erodes B layer (and Mo/W underneath) more quickly than NBI or Ohmic heating
  - Erosion localized to small fraction of PFC surfaces

- ITER operation with only tungsten walls is still uncertain
  - Core high-Z concentration (and radiation)
  - Boronization needed?
  - Melting still a concern

![Graph showing impurity concentration (CZ = nZ/ne) vs discharges after boronization for different tokamaks.](image-url)
Summary

• We are making progress towards first-principles prediction of transport
  ▪ Much better understanding of parallel transport in the SOL
  ▪ Connection of radial transport to underlying turbulence
• Tritium retention rate estimated to be lower than before but still uncertain
  ▪ Combined Be/W/C reduces T retention over pure carbon
  ▪ A number of T removal techniques being explored with success
• Transient loading on PFC surfaces is very complicated
  ▪ Most disruptions have reduced stored energy before the thermal quench
  ▪ Disruption mitigation is better understood - more confidence in application to ITER
  ▪ Type I ELMs lead to localized heating and erosion of first-wall components
• Material characteristics and their interactions are a central emphasis
  ▪ A variety of alloys are created whose behavior is difficult to include in predictions
  ▪ High-Z operational experience shows an important role for boronization