Transport
ELMs & disruptions
D/T retention & removal
Materials
Summary
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 material (e.g. boronization)</td>
<td>No boronization planned (but Be may serve that purpose)</td>
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<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

- ITER parallel power flow width similar (normalized to R) to current tokamaks.

\[ Q_{\parallel} \propto P/R^2 \text{ NOT } P/R \]
We are building a basic understanding of radial transport in the SOL

- Pressure gradients just outside the separatrix are well-organized by Electromagnetic Fluid Drift Turbulence parameters => direct connection between gradients and underlying turbulence.

=> Potential to predict plasma profiles from first principles.

=> ITER parallel power flow width similar (normalized to R) to current tokamaks.

=> Q|| ∝ P/R² NOT P/R
Much better understanding of flows in the edge

SOL flows are a controlling process in impurity transport as well as tritium co-deposition

• Standard models predict ~ stagnant flows in the SOL opposite the divertor
Much better understanding of flows in the edge

SOL flows are a controlling process in impurity transport as well as tritium co-deposition

• Standard models can’t match measured flows
• New inner wall probe measurements provide clues:
  ■ Pressure drop from from low- to high-field SOL
  ■ M~1 flows at high field side*

* LaBombard, Phys Plasmas 12 (2005)
Much better understanding of flows in the edge

SOL flows are a controlling process in impurity transport as well as tritium co-deposition

• Standard models can’t match measured flows
• New inner wall probe measurements provide clues:
  ■ Pressure drop from from **low- to high-field SOL**
  ■ Pressure imbalance => driving parallel flows
  ■ 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**

* Gunn, EX/P4-9, LaBombard, Phys Plasmas 12 (2005)
ELM filaments travel far through the SOL to the wall

Type I ELMs reduce ITER divertor and main chamber PFC lifetime†

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

†Loarte, IT/P1-14, Boedo, EX/P4-2, *Kirk, EX/9-1

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Type I ELMs reduce ITER divertor and main chamber PFC lifetime†

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

†Loarte, IT/P1-14, Boedo, EX/P4-2, *Kirk, EX/9-1
Type 1 ELM filaments lead to variable heat loads on first wall surfaces

- 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*

Type 1 ELM filaments lead to local hot spots on limiters

- The instantaneous heat load is high.

Heat loads are less localized when averaged over ELMs

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

• ELMs need to be small enough such that the divertor survives ($\Delta W_{\text{ELM}}/\Delta W_{\text{PED}} < 5\%$) - then main chamber surfaces should be ok too**.

• But, a few strong ELMs can reduce the tile resistance to thermal shock

• The community is pursuing small ELM regimes as well as ELM mitigation***.

**Loarte et al, Paper IT/P1-14, ***Moyer et al, Paper EX/9-3
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 for ITER reference scenario
- Advanced scenario (ITB and high-β) disruptions are the most dangerous: All the stored energy comes out rapidly
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- => specify fewer ITER high power disruptions for ITER reference scenario

- Advanced scenario (ITB and high-β) disruptions are the most dangerous: All the stored energy comes out rapidly

- The divertor receives less of the disruption energy as the stored energy increases

- Surfaces outside the divertor become more of a concern

- Disruption mitigation is being pursued with success*

\*Granetz, EX/4-3, Pautasso, EX/P8-7, Izzo, TH/P3-15

ITPA SOL/divertor presentation, 2006, Chengdu
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 retention of 0.1% needed for continuous operation
  - ITER will have much less carbon, replaced with Be and tungsten (W).
  - Be does co-deposit with tritium but releases it at a lower temperature than C
  - Be will not migrate to remote cooled locations as easily as carbon =&gt; less likely to accumulate thick co-deposited layers
  - Predicted to lead to lower T retention than current tokamaks

=&gt;Modelling estimates give a range of 1-3 weeks operation before T site limit reached
T retention on tile sides could 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 over current carbon PFC tokamaks
T retention on tile sides could be more important in ITER

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- Cross-tokamak studies indicate tile side D retention
  - Proportional to surface ion fluence
  - Lowest in fully high-Z tokamak
  - Reduced by elevated tile temperatures
- More difficult to remove
Studies have revealed another process besides co-deposition that leads to T retention

- A number of tokamaks have reported that co-deposition on tile surfaces 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
  - Exploring for Be, W as well

*Loarer, EX/3-6. **Whyte, EX/P4-29
Mixed materials in ITER are a mixed blessing

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

- Be or W on carbon surfaces reduces carbon chemical sputtering

- Carbon tiles could even be doped with metals before installation such that the chemical erosion is reduced

![Chemical Erosion Yield (C/D) vs Temperature (K)](image-url)
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 & T (Oxygen exposure, discharge cleaning…)
  ■ Ablation of the carbon - freeing the T (e.g. flash-lamps, lasers)

• All techniques must
  ■ Remove T from wherever it is stored (tile front, sides, bulk)
  ■ Be compatible with ITER toroidal field
  ■ Not cause dust
  ■ Be able to remove T from mixed material surfaces such as
    ● Be, W, C, BeC, WC, Be$_2$W
  ■ Not cause problems for subsequent operation
    ● Impurities or damage to vessel
ITER operation with high-Z PFCs is a goal in support of DEMO

- Tokamaks with primarily high-Z PFCs
  - ASDEX-Upgrade (85% W-coated carbon)
  - C-Mod (100% solid Mo tiles)
- Core high-Z content rises quickly after boronization*
- ICRF erodes B layer (and Mo/W underneath) more quickly than NBI or Ohmic heating
- Erosion localized to small fraction of PFCs

- Questions remain
  - Core high-Z concentration (and radiation)
  - Boronization needed?
  - Melting

*Dux et al, EX/3-3, Marmar et al, EX/3-4
Better understanding but uncertainties are still a concern

• We are making progress towards first-principles prediction of transport
  ■ Much better capability of predicting parallel transport (and impurity transport)
  ■ 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 are being explored with success

• Transient loading on PFC surfaces is very complicated
  ■ Much of the stored energy can be lost before disruption thermal quench
  ■ The loading of first-wall surfaces by ELMs and disruptions is uncertain

• Material characteristics and their interactions strongly affect ITER operation
  ■ A variety of alloys are created whose behavior is difficult to include in predictions
  ■ High-Z operational experience for ITER is being developed
The Interaction with the first-wall is central to the success of ITER

We cannot afford to ignore problems

Nor can we say: ‘the sky is falling’