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Plasma-Wall Interaction Issues in ITER.

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Plasma-Wall Interaction
Issues in ITER

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M. Shimada, ITER Organization
special acknowledgement: J. Roth
Fusion power: 500 MW, $Q = \frac{P_{\text{fusion}}}{P_{\text{aux}}} > 10$, $\frac{P_{\alpha}}{P_{\text{heat}}} > 0.8$, burn time = 300-500 s
Steady state (burn time $\sim3000$ s), $Q > 5$
## ITER Operation Schedule (Provisional)

<table>
<thead>
<tr>
<th>Mile Stone</th>
<th>Construction Phase</th>
<th>1st yr</th>
<th>2nd yr</th>
<th>3rd yr</th>
<th>4th yr</th>
<th>5th yr</th>
<th>6th yr</th>
<th>7th yr</th>
<th>8th yr</th>
<th>9th yr</th>
<th>10th yr</th>
</tr>
</thead>
</table>
| Installation & Commissioning | Basic Installation | - Commissioning  
- Achieve good vacuum & wall condition | - For activation phase | - For high duty operation | - Upgrade |
| Operation | - H Plasma Phase | - Machine commissioning with plasma  
- Heating & CD Exp.  
- Reference scenarios with H | - D Phase | - First DT Plasma Phase | - Low Duty DT | - High Duty DT |
| Equivalent Number of Burn Pulses (500 MW x 440 s*) | 1 | 750 | 1000 | 1500 | 2500 | 3000 | 3000 |
| Fluence** | 0.006 MWe/m² | 1.000 MWe/m² | 1.500 MWe/m² | 2.500 MWe/m² | 3.000 MWe/m² | 3.000 MWe/m² |
| Blanket Test | - Electro-magnetic test  
- Hydraulics test  
- Effect of ferritic steel etc. | - Neutronics test  
- Validate breeding performance | - Short-time test of T breeding  
- Thermo-mechanics test  
- Preliminary high grade heat generation test, etc. | - On-line tritium recovery  
- High grade heat generation  
- Possible electricity generation, etc. |

* The burn time of 440 s includes 400 s flat top plus 40 s of full power neutron flux to allow for contributions during ramp-up and ramp-down

** Average fluence at first wall (neutron wall load is 0.56 MW/m² on average and 0.77 MW/m² at outboard equator)
Challenges in ITER

• Important step toward Demo
  – Demonstration of Q>10, long burn and Q>5 steady state
  – Avoidance or significant mitigation of disruptions and ELMs
  – Test of reactor-relevant PFCs (tungsten)
• Large stored energy (350 MJ/~10MJ in JET & JT-60U)
  – Consequences of disruption and ELMs are much more serious
• Nuclear
  – Control of T retention and dust essential
• Long pulse, steady state
  – PFCs will be saturated with DT: start-up?
• Diagnostics
  – Limited access, irradiation-induced effects, first-mirror coating…
Contents

• ITER
• PWI issues
  – Impurity
  – Heat loads and erosion
  – Tritium retention
  – Material
  – Dust
• summary
Tokamak divertor configuration

- Separatrix (i.e. LCFS)
- Closed magnetic surfaces
- Open magnetic surfaces
- Scrape-off layer
- Strike points
- X-point
- Divertor plates
- Private plasma
Impurity

• Radiation
  • radiation in the core is detrimental for confinement
    \[ \frac{dW}{dt} + \frac{W}{\tau_E} = P_{\text{heat}} - P_{\text{rad}} \]
  • e.g., with tungsten concentration of \( >10^{-5} \), H-mode confinement cannot be sustained
  • radiation in the divertor is beneficial for reduction of divertor heat load

• Dilution
  • electron density has a limit
    \[ n_e = n_{DT} + \sum Z_i n_i \]
  • too much impurity would reduce the fuel density and fusion power
Impurity accumulation in the core

H. Takenaga et al., NF 43 (2003) 1235

with ITB

without ITB

\[ Z_{\text{eff}} - 1 \sim \frac{P_{\text{rad}}}{n_e^2} \]

Impurity density roughly uniform in the absence of an ITB

ITB acts as a barrier for impurity transport as well as for transport of fuel ions and energy

Inward velocity of impurities (neoclassical and turbulent pinch) overcomes outward diffusion

Impurity accumulation increases with ion charge

Cause for concern for both medium and high-Z impurities

W. Fundamenski, PSI-2008
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Divertor configuration and PFCs
New Understanding of Intermittency

- 2D fluid turbulence simulations reproduce some scaling and dynamics

2D electrostatic fluid turbulence simulations of TCV midplane SOL plasma (ESEL code, Risø) - successfully benchmarked against turbulence measurements


Russell et al, PoP 2006
Turbulence Imaging at Outboard Midplane and Lower X-pt Region

Midplane Characteristics:
- intermittent/bursty
- not seen at inboard midplane
- blobs roughly circular ~1 cm diam
- blobs co-exist with potential pert. that has dipole spatial structure
- blobs are X-sects of filaments

Lower X-pt-region Characteristics:
- bursty/intermittent
- finger-like structure
- fingers very tilted wrt hor.
  in lower part of image
- motion perp to flux surfaces
Lifetime of PFCs

Erosion assessment from laboratory data:

- Sputtering theory
- Experimental data
- MD Simulations

Physical sputtering understood and well predictable

Chemical sputtering widely investigated and well described

The multi-step process can be strongly modified by material mixing


300 K
Core-Edge-SOL Interplay

- Turbulence and transport lower in H-mode
- Fueling to the SOL is reduced
- Edge turbulence stabilization by Velocity Shear leads to H-mode

R. Moyer, et al, JNM, 96
C. Ritz, et al; Hidalgo et al, Endler et al

J. Boedo et al, PRL 99, Taylor et al
Weynants et al; Jachmich et al
Tynan et al,
**Lifetime of PFCs**

**Wall erosion in steady state:**

Be first wall erosion is calculated based on B2-Eirene results. Toroidal peaking may reduce wetted area to ≈ 50m².

For W erosion due to impurity sputtering is taken into account; here: 0.1% Ar in SOL plasma.

<table>
<thead>
<tr>
<th>Wall material</th>
<th>nm/s</th>
<th>atoms/s</th>
<th>g/shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be average</td>
<td>0.12</td>
<td>8 x 10²¹</td>
<td>48</td>
</tr>
<tr>
<td>peak 50m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W average</td>
<td>0.05</td>
<td>2 x 10²⁰</td>
<td>26</td>
</tr>
<tr>
<td>peak poloidal</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Erosion of Be first wall may become a lifetime problem for inhomogeneous loading.

Be erosion flux (m⁻² s⁻¹)

- 1.000E18
- 1.334E18
- 1.778E18
- 2.371E18
- 3.162E18
- 4.217E18
- 5.623E18
- 7.499E18
- 1.000E19

K. Schmid PSI-2008
CFC divertor erosion is calculated using ERO based on B2-Eirene results (including 0.1% Be\(^{2+}\), but reduction of chemical erosion due to Be not included).

W erosion mainly due to Ar impurities (0.1%) (DIVIMP)

<table>
<thead>
<tr>
<th>Divertor mat.</th>
<th>nm/s</th>
<th>atoms/s</th>
<th>g/shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC gross</td>
<td>100</td>
<td>4x10(^{22})</td>
<td>330</td>
</tr>
<tr>
<td>net</td>
<td></td>
<td>4x10(^{20})</td>
<td>3</td>
</tr>
<tr>
<td>W gross</td>
<td>2</td>
<td>4x10(^{20})</td>
<td>48</td>
</tr>
<tr>
<td>net</td>
<td>0.3</td>
<td>6x10(^{19})</td>
<td>7</td>
</tr>
</tbody>
</table>
Two sets of coils produce a variety of RMPs in DIII-D

- The 4-turn C-coil and single-turn upper/lower l-coil can be configured for n=3 RMP experiments or n=1 field-error correction
Particle transport is enhanced during the RMP pulse.

- $W_{\text{MHD}}$ drop is due to the density pump-out
- $W_{\text{MHD}}$ drop often much smaller
- Significant density pump-out
- $\tau_p^*$ reduced 6x at start of RMP pulse, 1.5–2x in steady state

$\tau_p^*$: E.A. Unterberg Paper P2-01

Moyer PSI08 – 7
ELM induced erosion: CFC

Results from Russian plasma simulators:

- Erosion limit for CFC reached due to PAN fibre erosion
- Erosion limit for W reached due to melting of tile edges

Crack formation was observed at energy densities $\geq 0.7$ MJ/m$^2$. Repetitive sub-threshold ELM investigations ongoing in JUDITH2

Recommended threshold for damage $0.5$ MJm$^{-2}$ ⇒ adopted by ITER

Efficient mitigation methods needed
Vapour shielding reduces CFC evaporation by factor 10
S. Pestchanyi PSI-2008

Predicted ITER disruptions exceed the 300 disruptions lifetime limit for W

Efficient mitigation methods needed

ITER assumptions:
30 disruptions in about 2000 discharges
10 % of melt layer lost in the case of W divertor plates
5 kg erosion per disruption

Federici, Strohmayer RACLETTE
Riccardo, Federici Nuclear Fusion 2005
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Erosion determines co-deposition:

- Rough estimate: total net erosion rate x co-deposition concentration
- Detailed evaluation: impurity transport including re-erosion, co-deposition concentration depending on final deposition conditions

Co-deposition with C and Be depends on deposition conditions: energy, deposition rate, temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>Erosion Rate (atoms/s)</th>
<th>Mass (g/shot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be wall</td>
<td>$3 \times 10^{20}$</td>
<td>1.8</td>
</tr>
<tr>
<td>CFC divertor</td>
<td>$2 \times 10^{21}$</td>
<td>3.2</td>
</tr>
<tr>
<td>W divertor</td>
<td>$4 \times 10^{17}$</td>
<td>$8 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Sum of both processes: comparison of materials options

Review for PPCF, submitted March 2008
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Plasma Facing Material Choice

- In the initial operation ITER uses beryllium FW, tungsten divertor baffle and dome, and carbon target plates to maximize the operation flexibility
- Before DT operation, the divertor target will be changed to tungsten to minimize the tritium retention
- Scenarios with Be/W PFC must be developed
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Dust generation

Potential safety concerns:

Potential release in environment

- W is the major radioactive source
- Dust contains trapped Tritium

Hydrogen production when hot dust reacts with steam

- Be major contributor
  - with carbon: $\Rightarrow 6$ kg C, $6$ Be, $6$ kg W limit
  - without carbon: $\Rightarrow 11$ kg Be, $230$ kg W limit

Possible pure Dust or Hydrogen/Dust explosion

- Be, C, W involved
Dust generation

Total dust generation:

Assumption:
- Dust generation dominated by erosion, deposition, layer disintegration
- Conversion from erosion to dust for safety reasons: 100 %
  (about 10 % in Tore Supra and JT-60U)

Total dust limit not reached before scheduled maintenance and exchange of divertor cassettes

What fraction of dust resides in hot (>600°C) areas?
Dust generation

Dust on hot areas:

Assumption:
- On hot plasma (>600°C) wetted areas deposits and dust will only survive in castellation
- Need to estimate the fraction of impurity deposition in gaps from experimental data base see A. Litnowski PSI-2008

Assume dust at hot area collects only in gaps:

Flux of Be to outer target hot zone (DIVIMP):
\[ 2 \times 10^{19}/m^2s \]

Area of hot zone: 8m²

⇒ Total Be flux: \[ 1.6 \times 10^{20}/s \approx 1g/disch \]

Gap area 2%

⇒ Hot Be dust rate: 0.02g/disch

⇒ 11kg Be dust for W/Be wall in 60000 disch.

If tungsten dust is produced on hot surfaces in the order of a few kg, significant cleaning efforts must be made before the next operation (the acceptable amount of tungsten in the core is ~0.2 mg)
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Summary

• To facilitate ITER operation, R&D in following areas are essential
  – Avoidance or significant mitigation of disruptions/VDEs and ELMs
  – Development of scenarios with Be/W PFCs
  – Control of T retention and dust
  – Development of understanding of sol transport during steady state and off-normal events
  – Development of wall conditioning scenarios
Useful Free URLs

Invited talks at PSI-2008 (International Conference on Plasma Surface Interactions in Controlled Fusion Devices):

Proceedings of IAEA Fusion Energy Conferences:

Progress in the ITER Physics Basis (comprehensive review paper ~400 pages):
http://www.iop.org/EJ/toc/0029-5515/47/6
Volume 47, Number 6, June 2007

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PROGRESS IN THE ITER PHYSICS BASIS

PREFACE

Progress in the ITER Physics Basis
K. Ikeda

Full text | Citing articles

Full text: Acrobat PDF (68.4 KB)

Chapter 1: Overview and summary
M. Shimada, D.J. Campbell, V. Mu
Wesley, N. Asakura, A.E. Costley, A.
Houlberg, S. Ide, Y. Kamada, A. Li
A.C.C. Sips

Abstract | References | Citing articles

Full text: Acrobat PDF (1.96 MB)

Summary: Chapter 1