Plasma wall interactions in tokamaks: When the 4th state of matter meets the other 3

E. Tsitrone, CEA-IRFM
Task Force leader of the EU Plasma Wall Interaction Task Force

"The boundary edge is where the stellar world of hot plasmas meets the earthly world of cold solids. Understanding the complex interaction of these two worlds is essential for operating a fusion reactor successfully."

Wojtek Fundamenski, JET TF Leader
Outline

• Fusion basics
• On the road to fusion performance: ITER
• Plasma wall interactions: overview
• Challenges for ITER
  • Plasma facing components lifetime
  • Material migration, fuel retention, dust
  • Diagnostics and modelling
• An ambitious worldwide programme
• Summary
Fusion basics
What is fusion?

The energy of the stars ...
Fusion on earth: using D-T

\[ T \sim 20 \text{ keV} \rightarrow \text{plasma} \]
Fusion on earth: the magnetic trap

Toroidal field

Poloidal field

Total field

- Tokamak:
  - external coils → toroidal field
  - plasma current $I_p$ → poloidal field
Alternative configuration: the stellarator

- Toroidal + poloidal field: external magnetic field coils
Why do we bother?

• Almost limitless fuel supply

\[
D + T \rightarrow {}^4\text{He} + n
\]

\[
{}^6\text{Li} + n \rightarrow {}^4\text{He} + T
\]

• No greenhouse gas emission

• Intrinsically safe
  • No chain reaction
  • Only few g of fuel → enough for a few s burn

• No long term radioactive waste:
  • not from reaction products (He)
  • activation of the vessel (n): low activity materials
On the way to fusion performance: ITER
How does it produce energy?

Fusion power amplification:

\[ Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E \]

Density (\( n_i \)):

\( 1 \times 10^{20} \text{ m}^{-3} \)

(of atmospheric particle density)

Temperature (\( T_i \)):

\( 1-2 \times 10^8 \text{ °C} \)

(\(~10 \times \text{temperature of sun’s core}\))

Energy confinement time (\( \tau_E \)): few seconds

(plasma pulse duration ~1000s)

⇒ Present devices: \( Q \leq 1 \)

⇒ Next step: ITER: \( Q \geq 10 \)

⇒ Future Reactors: \( Q \geq 30 \)
Density: fuelling the plasma

- **Gas injection**: easy, poor efficiency

- **Pellet injection**: complex, high efficiency
Temperature: heating the plasma

Future reactor: Heating by the alpha’s
Confinement

Tokamak transport $\rightarrow$ collisions $\rightarrow$ turbulence

L mode: low confinement
H mode: high confinement

$\tau_{E}$

i) Advanced Operating Modes
- Internal Transport Barrier (ITB)
- Edge Transport Barrier (ETB) (H-mode)
- Edge Localized Modes (ELMs)

ii) H-mode
- Sawteeth

$\tau_{th}$ (s)

Plasma Pressure

Normalised radius $r/a$
The fusion quest

60's: tokamak concept developed

Q = 1, Break-even

- JET: Joint European Torus, England
- ASDEX upgrade, TEXTOR, Germany
- Tore Supra, France
- MAST, England
- TCV, Switzerland
- JT60U, Japan
- DIII-D, USA
- Alcator CMod, USA
- EAST, China
- KSTAR, South Korea
- SST1, India

+ …
Next step: the ITER project

ITER is a major international collaboration in fusion energy research involving the EU (plus Switzerland, Romania, Bulgaria), China, India, Japan, the Russian Federation, South Korea and the United States.

• Programmatic objective:
  • to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes
  • produce a significant fusion power amplification \((Q \geq 10)\) in long-pulse
  • aim to achieve steady-state operation of a tokamak \((Q = 5)\)

⇒ a burning plasma experiment

ITER Agreement Signature, Elysee Palace, 21.11.2006
ITER : an ambitious challenge

ITER is twice as large as our largest existing experiments

Tore Supra (France)
- \( V_{\text{plasma}} \approx 25 \, m^3 \)
- \( P_{\text{fus}} \approx 0 \, MW \)
- \( Q<1 \)

JET (UK)
- \( 80 \, m^3 \)
- \( \approx 16 \, MW \)
- \( Q=0.5 \)

ITER (France)
- \( 830 \, m^3 \)
- \( \approx 500 \, MW \)
- \( Q>10 \)

1990               2008        2016                      2036

Design       Construction      Exploitation

Q \geq 10

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Main PWI issues for ITER: [R. Pitts]

- Plasma Facing Components lifetime:
  - steady state $\rightarrow$ radiation cooling (impurity seeding) [M. Merola]
  - ELMs and disruption $\rightarrow$ mitigation [A. Loarte]

- Fuel retention (T inventory) [P. Andrew, R. Causey, T. Tanabe]

- Dust production [P. Andrew]
Plasma wall interactions: overview
Edge plasma:

- exhaust heat fluxes (~ 10 MW/m²)
- exhaust the reaction ashes (He)
- without perturbing core plasma performance (impurities)
Plasma facing components (PFCs): Limiter and divertor

Limiter

Last closed flux surface

Confined plasma

Limiter

DIVERTOR

Last closed flux surface

Strike points

Confined plasma

SOL

Divertor plasma

Divertor target plates

H mode (ELMs)
Plasma Wall Interactions

Plasma ➔ wall (heat and particle load ➔ erosion, PFCs lifetime)

- Space: Strong localized interactions with divertor targets
- Time: Steady state loads + transients (ELMs, disruptions)

➔ Radiation cooling

Wall ➔ plasma (pollution ➔ plasma performance)

Material migration

Erosion ➔ Transport ➔ Deposition ➔ Shadowed area

Re-erosion

[J. Strachan]

Strong heat and particle flux (divertor)

Erosion ➔ PFC lifetime

Redeposition ➔ fuel retention and dust: safety issues
What is the ideal material?

Low Z materials (carbone, beryllium):
- erosion / pollution / fuel retention

High Z materials (tungsten):
- erosion / pollution / fuel retention

Low Z materials (carbone, beryllium):
- chemical erosion
- threshold
- core

Few % of C

Few $10^{-5}$ of W

E. Tsitrone
ITER summer school on PWI 22-26/06/2009
First wall: Be (700 m²)
- moderate heat flux
- low Z, oxygen getter: control of impurity content
  $\Rightarrow$ plasma performance

Divertor baffles + dome: W (100 m²)
- medium heat flux
- high erosion threshold
  $\Rightarrow$ life time + T retention

Divertor targets: Carbon Fiber Composite (50 m²)
- high heat flux
  Excellent thermo-mechanical properties, low Z
  $\Rightarrow$ heat flux handling in divertor

ITER second phase of operation:
- W divertor / Be wall
Plasma recycling

- Plasma hitting a surface recombine $\rightarrow$ neutrals
- Complex atomic and molecular physics: dissociation, charge exchange, ionisation
- If re-ionisation $<\text{LCFS}$, re-start the process ... : recycling
Impurities also ...

- Plasma hitting a surface → erosion → impurities
- Atomic and molecular physics processes: photons
  - radiation cooling (edge)
  - Diagnostics (spectroscopy)
The sheath potential

\[ v \propto \sqrt{kT / m} \quad m_e \ll m_i \Rightarrow v_e \gg v_i \]

Potential: \( \Phi = 3 \, kT_e \)

Ion impact energy: \( 2T_i + 3 \, Z \, kT_e \)
- threshold for erosion
- power on surface

[W. Fundamenski, R. Pitts]

+ Complex poloidal and // flow pattern in SOL
Power handling

\[ \lambda_Q \sim 1 \text{ cm} : \text{power concentrated in the near SOL} \]

\[ \text{exponential decay in the SOL} \]

\[ \Gamma_{//}, \Gamma_{\perp} : \text{~} \]

PFC design:
- grazing incidence
- avoid leading edge

\[ Q_{//}, Q_{//} \sin \alpha \]

E. Tsiirone

ITER summer school on PWI 22-26/06/2009
PWI challenges for ITER: Plasma facing components lifetime
Steady state loads

- Power to exhaust on PFCs $\sim$100 MW
  - $Q = 40$ MW / m$^2$
  - Radiation cooling needed

- ITER reference scenario:
  - Partially detached plasma
  - Extrinsic impurity seeding (Ar, Ne ..)
  - $Q = 10$ MW/m$^2$
  - Active cooling of PFCs

- Thermal shield for space shuttle
  - Technology $\sim$ ok
  - [M. Merola]
Detached plasma in TS

ITER : partial detachment
Transient heat loads

ELMs: 5-10 MJ/m$^2$ during 250-500 µs
Disruptions: 5-15 MJ/m$^2$ during 1.5-3 ms

Material damage:
Plasma guns ➔ new limit 0.5 MJ/m$^2$
Hard constraint on scenario (~ELM size / 20)

[A. Loarte]
Neutrons

- ITER end of life ~ 1 dpa (neutrons 14 MeV)
- CFC thermal properties degraded, W ok
- Next step (reactor) : IFMIF project

[L. Snead]
PWI challenges for ITER: material migration, dust and fuel retention
Material migration

- Divertor:
  - Outer divertor: erosion
  - Inner divertor: redeposition

- Mixed materials:
  - Be-W alloy: melting point closer to Be than W

[K. Krieger]

[Y. Ueda, N. Yoshida, G. Tynan]
Fuel retention

Safety limits for T inventory:
- 1 kg (risk = release in environment)

- Implantation: a few nm
- Diffusion: far into the bulk (µm)?
- Erosion (phys. or chem.)
- Co-deposition

Bulk diffusion:
Main mechanism for W

Codeposition:
Main mechanism for CFC, Be

Retention:
W << Be < CFC

Fuel removal:
Photonic methods (laser)
Chemical methods (cleaning discharges)
Dust

Safety limits for dust:
- 1000 kg (risk = release in environment)
- 18 kg on hot surfaces (risk = H production)

Dust production:
- Thick layers flaking
- Transients
- Maintenance, cleaning ...

Pb for operation before safety?

Dust removal techniques:
- Electrostatic removal, vacuum cleaning, flush with liquids, laser

[R. Pitts, P. Andrew]
PWI challenges for ITER: Diagnostics and modelling
Diagnostics and modelling

Diagnostics: measure and control:
- Plasma properties (ne, Te, impurities …)
- Heat fluxes on PFCs
- Dust and fuel inventory (safety)

[S. Pitcher]

Modelling: understand and extrapolate
- Plasma transport
- Heat fluxes on PFCs
- Erosion, material migration, fuel retention …

[T. Tazikuka, M. Kobayashi, K. Ohya]

graphite limiter

injection hole \(^{13}\text{CH}_4\)

local deposition

ERO modelling

\begin{align*}
\text{x (toroidal direction)} [\text{mm}] & : & \text{y (poloidal direction)} [\text{mm}] \\
1.0 \times 10^{17} & : & 1.0 \times 10^{15}
\end{align*}
Plasma wall interactions: An ambitious programme worldwide
International Tokamak Physics Activities on Divertor and Scrape off layer
Experts from the 7 ITER partners

Annual meeting 2005 : on the ITER site
Meeting may 2009 : Amsterdam

European Task force on Plasma Wall Interactions
24 associations (~ 80 ppy)
http://www.efda-taskforce-pwi.org/
Complementary PWI programmes

**TEXTOR : Flexible PWI tools**
- First wall (boronised)
- Inner bumper
- Outboard limiters
- Toroidal limiter
- Inner bumper
- Toroidal pump limiter (TPL)

**AUG : Pioneering W operation**
- Divertor
- Outboard limiters
- Inner Shield

**Tore Supra : Steady state PWI (Tsurf)**
- Steady state PWI (Tsurf)
- Inner panels
- Outer bumper
- Vessel protection panels
JET ITER like wall

JET ITER like wall: W divertor (coatings + bulk W)
Be first wall

Shutdown for installation of JET ITER like wall starting end 2009
Summary

Plasma wall interactions: interdisciplinary field

- Plasma physics (edge: sheath, 3D!)
- Atomic and molecular physics
- Plasma-wall interactions (erosion ...)
- Solid state physics (wall: fuel retention, mixed material)

Edge plasma: a central question for fusion devices

- Exhaust the heat
- Exhaust the ashes (He)
- without perturbing the core plasma (impurities)

PWI issues for ITER

- Plasma Facing components lifetime
  - Minimize thermal loads (PFC design, radiation cooling)
  - Mitigate transients (ELMs, disruptions)
- Tritium retention / Dust production
  - Develop diagnostics (safety), implement fuel/dust removal techniques

A coordinated program at the international and European level: welcome!
(Selected) useful references

Book:

Overview papers:

“Plasma-material interactions in current tokamaks and their implications for next step fusion reactors”, G. Federici et al., Nucl. Fusion 41 (2001) 196

“ITER Physics basis: Chapter 4, power and particle control”, Nucl. Fusion 39 (1999) 2391


“Recent analysis of key plasma wall interactions issues for ITER”, J. Roth et al., J. Nucl. Mater. 390-391 (2009) 1

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