Spectroscopic applications for plasma-wall interaction observations in fusion devices

Kalle Heinola

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Outline

1. Introduction
   a) tokamak plasma-wall interactions
   b) diagnostic tools

2. Spectroscopic applications in plasma edge
   a) erosion of Be wall material
   b) material migration
   c) plasma-induced erosion of W

3. Divertor spectroscopy and ELMs
   a) ELM-induced erosion of W
   b) plasma-material interactions and ELMs
   c) fuel retention and effect of ELMs
1.a tokamaks and PWI

- Present day fusion devices to study plasma properties & plasma-wall interactions (PWI): plasma-surface (PSI) & plasma-material interactions (PMI)
  - Experimental results transferred/extrapolated to larger devices
  - Plasma power and intensity of PWIs increase with machine size
    - Modelling & simulations play a crucial role
    - Models to cope with DEMO & Fusion Power Plant conditions
    - Plasma physics (A+M data!) and materials science

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**JET**
- Plasma pulse: few secs to tens secs
- Volume: 100 m³
- Fusion P: 16 MW (Q~0.67)
- Neutron damage: <<1 dpa
- Particle fluence: \(~10^{24}\) m⁻²

**ITER**
- Pulse: 400 sec
- Volume: 840 m³
- Power: 500 MW (Q≥10)
- Neutron damage: < 2 dpa
- Particle fluence: ~10²⁷ m⁻²

**DEMO1**
- Pulse: > 2 hours
- Volume: ~2500 m³
- Power: 2200 MW (Q~30-50), grid 500 MW
- Neutron damage: up to 20-50 dpa
- Neutral particle fluence: ~10²⁷ m⁻²

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1.a tokamaks and PWI

- plasma monitoring and control
  - plasma magnetically confined → drifts, etc → plasma-wall interactions (PWIs)
1.a tokamaks and PWI

- plasma monitoring and control
  - plasma magnetically confined $\rightarrow$ drifts, etc $\rightarrow$ plasma-wall interactions (PWIs)
  - distinguishable plasma regions:
    1. core (closed $B$ lines):
      - plasma particles confined with $B$
      - ionized particles and $e^{-}$ traverse on helical trajectories around torus
      - energy: up to tens keV
      - collision processes and fusion
      - monitoring of plasma shape, density, temperature, …
    2. scrape-off layer (SOL; edge; open $B$ lines):
      - region of plasma exhaust: particles escaped the core
      - energy: tens of eV (divertor: ELMs several keV)
      - monitoring density, temperature, …
      - interaction with the surrounding components: Wall lifetime, fuel recycling & retention
1.b diagnostics: core

- plasma core

- several plasma parameters to be monitored
  - particle temperatures $T_i$, $T_e$
  - particle densities $n_i$, $n_e$
  - plasma shape, flows, and fluctuations

- tens of plasma diagnostics (active and passive)
  - $T_i$, $n_i$: radiation emitted in charge-exchange (CX) processes with injected neutral plasma particles; radiation emission collisions as X-rays, $\gamma$-rays
  - $T_e$, $n_e$: Thomson scattering (laser); electron cyclotron emission (ECE; passive)
  - radiated power: bolometers

- e.g. $T_e$, $n_e$ in JET (core and edge):

  - ECE – Electron Cyclotron Emission
  - HRTS – High-Resolution Thomson Scattering
  - LIDAR – Light Detection and Ranging (Thomson)
1.b diagnostics: SOL and wall

- plasma edge
  - monitoring of plasma SOL/edge and wall surface
    - particle temperatures $T_i, T_e$
    - particle densities $n_i, n_e$
    - properties in the main chamber and in the divertor box:
      - wall temperature
      - impinging particles (energies, flux)
      - erosion
  
  ...
1.b diagnostics: SOL and wall

- plasma edge
  - monitoring of plasma SOL/edge and wall surface
  - edge plasma and wall diagnostics (active and passive)
    - spectroscopic measurements of particle + particle, particle + $e^-$, etc processes: XUV-VUV

e.g. JET various XUV-VUV spectroscopy (core and edge)
1.b diagnostics: SOL and wall

- plasma edge
  - monitoring of plasma SOL/edge and wall surface
  - edge plasma and wall diagnostics (active and passive)
    - spectroscopic measurements of particle + particle, particle + e\(^-\), etc processes: XUV-VUV optical emission
    - specific wall areas of interest covered with spectroscopy
      (JET: D, W, Be, hydrides. Seeded impurities N, Ar, Ne)
    - other: Langmuir probes for particle flux to wall; thermocouples; Quartz-micro balance; dust monitors; ...

  
  e.g. JET optical spectroscopy
1. diagnostics: JET

- Reciprocating probe (a)
  - 14MeV Neutron spectrometer
  - Edge LIDAR Thomson scattering
- Reciprocating probe (b)
- 2.5MeV Time-of-flight neutron spectrometer
- Fast ion and alpha-particle diagnostic
- High energy neutral particle analyser
- Neutron activation
- Active phase neutral particle analyser

- 14MeV Neutron spectrometer
- Active phase soft X-ray cameras
- Hard X-ray monitors
- Bolometer cameras
- Compact, VUV camera
- Compact, in-vessel soft X-ray camera
- Compact, re-entrant soft X-ray camera
- Time-resolved neutron yield monitor
- Bolometer cameras
- Hard X-ray monitors

- Time resolved neutron yield monitor
- Charge exchange recombination spectroscopy
- H-alpha and visible light monitors Brem

- X-ray pulse height spectrometer
- Grazing incidence XUV broadband spectroscopy

- O-mode microwave interferometer
- Electron cyclotron emission heterodyne

- Divertor gas analysis using Penning gauge
- High resolution X-ray crystal spectroscopy

- Divertor spectroscopy
- LIDAR Thomson scattering
- Fast ion and alpha-particle diagnostic

- VUV and XUV spectroscopy of divertor plasma
- 50kV lithium atom beam
- VUV spatial scan
- Multichannel far infrared interferometer

- Bragg rotor x-ray spectroscopy, VUV broadband spectroscopy
- Laser injected trace elements

- Neutron activation
- CCD viewing and recording

- Correlation reflectometer

- Neutron yield profile monitor and FEB
2.a Spectroscopy: Be wall erosion

- JET’s ITER-Like Wall experiment
  - all metal wall
  - Be limiters
    - thermal conductivity
    - impurity getter
    - $T_{\text{melt}} = 1287^\circ\text{C}$
  - W divertor
    - thermal conductivity
    - high erosion threshold
    - $T_{\text{melt}} \sim 3400^\circ\text{C}$
2.a Spectroscopy: Be wall erosion

- JET’s ITER-Like Wall experiment

Diagram:
- $X^+$, $X^0$, $e^-$
- Reflection
- Erosion
- Deposition
- Re-erosion
- Re-deposition
- Recycling
- Retention

Colors:
- Red: $D$ fuel
- Green: Be wall

Data from A+M/PSI

S. Brezinsek, Nucl. Fusion 54, 103001 (2014)
2.a Spectroscopy: Be wall erosion

- JET’s ITER-Like Wall experiment
  - Be main chamber limiters
  - W divertor

- D plasma interactions with limiters
  - Be erosion and material transport
  - determination of the amount of sputtered Be crucial

- In-situ optical spectroscopy emission of Be wall
  - line-of-sight to the plasma contact point
  - lines: Be II (527 nm, 467 nm 436 nm) and Dγ
  - Be erosion due to D⁺, excitation and ionization in collisions with plasma particles (e⁻, D⁺)

S. Brezinsek, Nucl. Fusion 54, 103001 (2014)
2.a Spectroscopy: Be wall erosion

- In-situ optical spectroscopy emission of Be wall
  - Be, D, and formation of D\(_2\), BeD observed
  - temperature effect
    - high \(T_{\text{base}}\) yields lower BeD
      - desorption of D as D\(_2\)
2.a Spectroscopy: Be wall erosion

- In-situ optical spectroscopy emission of Be wall
  - Be, D, and formation of D₂, BeD observed
  - Temperature effect
    - High $T_{\text{base}}$ yields lower BeD
      - Desorption of D as D₂
  - Be sputtering rate $Y_{\text{Be}}$:
    \[ Y_{\text{Be}} = 4\pi \frac{S I_{\text{Be}}}{X_B T_D} \]
    - Be II intensity
    - D⁺ flux to wall
    - (photon production)$^{-1}$

- Spectroscopic findings:
  - Be erosion increases with $T_i$
  - Different erosion mechanisms
  - Assessment for wall lifetime!
2.a Spectroscopy: Be wall erosion

- In-situ optical spectroscopy emission of Be wall
  - Be, D, and formation of D₂, BeD observed
  - temperature effect
    - high $T_{base}$ yields lower BeD
      - desorption of D as D₂

- Be sputtering rate $Y_{Be}$:

$$Y_{Be} = 4\pi \frac{S \times I_{Be}}{XB \times \Gamma_D}$$

- (photon production)$^{-1}$

- Spectroscopic findings:
  - Be erosion increases with $T_i$
  - different erosion mechanisms
  - assessment for wall lifetime!

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S. Brezinsek, Nucl. Fusion 54, 103001 (2014)
2.b Spectroscopy: divertor PSI

- D plasma-surface interactions in W divertor
  - W sputtering threshold by D approx. 250 eV
  - $T_e$ range low: eV...few tens of eV
    - W erosion unlikely due to D
    - wall eroded Be plays role?

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G. J. van Rooij, J.Nucl. Mat. 438, S42 (2013)
ICTP-IAEA School, Trieste 9.5.2019
2.b Spectroscopy: divertor PSI

- In-situ optical spectroscopy of W divertor
  - line-of-sight to W divertor
  - lines: W I (400.9 nm) and D\(\varepsilon\)
  - sputtered W get excited and ionized in collisions with plasma particles (e\(^-\), D\(^+\), impurities, ...)

- W sputtering rate \(Y_W\) :

  \[Y_W = 4\pi \frac{S}{XB} \frac{I_W}{\Gamma_D}\]

  - W I intensity
  - D\(^+\) flux to divertor
  - (photon production\(^{-1}\))

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  - lines: W I (400.9 nm) and D\(\epsilon\)
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- W sputtering rate \(Y_W\):
  \[
  Y_W = 4\pi \frac{S}{XB} \frac{I_W}{\Gamma_D}
  \]
  (photon production\(^{-1}\))

- Spectroscopic findings (low \(T_e\)):
  - W erosion: Be dependent, increases with \(T_i\)
  - measured 0.5% Be\(^{2+}\) corresponds to Be erosion
  - assessment for divertor sputtering
3.a Spectroscopy: divertor PSI w/ ELMs

- Plasma edge-localized modes (ELMs)
  - ELMs present in medium-sized to large devices (H-mode)
  - plasma pressure increase at pedestal
  - release to divertor → high heat and energetic particles!

Δt_{ELM} \sim ms range
3.a Spectroscopy: divertor PSI w/ ELMs

- Formation of magnetic configuration with plasma strike points in divertor

- Plasma strike points: highest particle & heat load

- Be- coated inconel PFCs
- Be coated PFCs
- W- coated CFC PFCs
3.a Spectroscopy: divertor PSI w/ ELMs

- Plasma edge-localized modes (ELMs)
  - ITER steady state 10 MW/m², slow transients 20 MW/m², particle $E_k \sim$ few tens eV
  - ELMs $\sim$ 1 GW/m², $\Delta t \sim$ 0.5 ms, $E_k$ of keV range
  - disruptions, VDEs, …

![Diagram showing PFC temperature and plasma pulse time with power levels 5 MW/m², 10 MW/m², and 20 MW/m².]
Plasma edge-localized modes (ELMs)
- ELMs present in medium-sized to large devices (H-mode)
- plasma pressure increase at pedestal
- release to divertor → high heat and energetic particles

- monitoring ELMs crucial
- diagnostic methods for $n_{e,i}$, $T_{e,i}$, temp., ...
- assessment of wall effects required
  - plasma operation
  - wall lifetime
  - fuel recycling and retention
3.a Spectroscopy: divertor PSI w/ ELMs

- *In-situ* optical spectroscopy of W divertor with ELMs
  - experiment with detached plasma
    (N$_2$ seeding for divertor plasma mitigation)

\[ T_e \downarrow \quad \text{as puffed} \quad N_2 \uparrow \quad \text{in divertor} \]
**3.a Spectroscopy: divertor PSI w/ ELMs**

- *In-situ* optical spectroscopy of W divertor with ELMs
  - experiment with detached plasma (N\(_2\) seeding for mitigation)
  - between ELMs (blue line): no W erosion
  - during ELM (red line): clear W I peak for erosion

- ELMy plasmas can sputter W efficiently
  - energetic D\(^+\) and impurities from the pedestal

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G. J. van Rooij, J.Nucl. Mat. 438, S42 (2013)
ELM-resolved $D^+$ impact energy ($E_i$) at W divertor
(unseeded plasma $\rightarrow$ no $N_2$, no mitigation)

- Why?
  - plasma with 0.5% Be$^{2+}$
  - $D^+$ dominant ELM component

- How?
  - *in-situ* $D\alpha$ spectroscopy $\rightarrow$ ion/s at target
  - ECE $\rightarrow$ maximum $T_e$ at pedestal ($T_{e,\text{max}}^{\text{ped}}$)
  - absorbed power at target
  - ELM impact energy at divertor correlates with $T_e$ in pedestal as ("Free stream model"): 
    \[ \max(E_i + E_e) \approx \alpha T_{e,\text{max}}^{\text{ped}} \]

- ECE power

(optical spectroscopy $W\ I$ and $D\alpha$)

3. Spectroscopy: divertor PSI w/ ELMs

- ELM-resolved $D^+$ impact energy ($E_i$) at W divertor
  - How?
    - *in-situ* $D\alpha$ spectroscopy $\rightarrow$ ion/s at target
    - ECE $\rightarrow$ maximum $T_e$ at pedestal ($T_{e,\text{max}}^{\text{ped}}$)
    - absorbed power at target
  - Result
    - $\max(E_i + E_e) \approx \alpha T_{e,\text{max}}^{\text{ped}}$ ($E_e = E_{e,\perp} = T_{e,\text{max}}^{\text{ped}}$)
    - $E_{i,\text{max}} \approx 4.23 T_{e,\text{max}}^{\text{ped}}$
    - JET: experimental $T_{e,\text{max}}^{\text{ped}} \approx 1$ keV results
      - $E_{i,\text{max}} \approx 3$ keV
      - $D^+$ in ELMs sputter W easily
      - $D^+$ sputters $20 \times$ more W than Be$^{2+}$

3.a Spectroscopy: divertor PSI w/ ELMs

- ELM-resolved D$^+$ impact energy ($E_i$) at W divertor
  - Result
    - $E_{i,\text{max}} \approx 4.23T_{e,\text{max}}^{\text{ped}}$
    - JET: experimental $T_{e,\text{max}}^{\text{ped}} \approx 1$ keV results
      in $E_{i,\text{max}} \approx 3$ keV
      → D$^+$ in ELMs sputters W easily
      → D$^+$ sputters 20× more W than Be$^{2+}$
    - ITER: theoretical $T_{e,\text{max}}^{\text{ped}} \sim 5$ keV → $E_{i,\text{max}} \sim 20$ keV

optical spectroscopy W I, Be II and Dα

-ogens

- diverted B lines

- $T_{e,\text{max}}^{\text{ped}}$

- $E_{i,\text{max}}$

- ions to divertor

- W sputt. total

- 9.5.2019
3.b Divertor PMI w/ ELMs

- Plasma-material interactions (PMI) below the surface of W divertor target

- Data from A+M

- Neutrons

- Vacancy & interstitial dislocation loop

- Vacancy & interstitial defects

- 3D extended defects

- Grain boundaries

- Retention

- Recycling

- Amorphisation
PMI events and reactions, and fuel retention simulated with multi-scale Rate Theory Equation calculations

- coupled partial differential equations (PDE) for physical processes in the bulk and on the surface

1) D processes inside W
   - diffusion
   - retention, trapping, re-trapping with defects
   - recycling

2) ELM-induced defect evolution inside W
   - nucleation
   - diffusion
   - clustering
   - dissociation
   - ...

→ over 300 entities which take part in 3200 exothermic and 300 endothermic reactions
3.c Divertor fuel retention w/ ELMs

- PMI events and reactions, and fuel retention simulated with multi-scale Rate Theory Equation calculations
  - PDE parametrisation: experiments and computational methods (ab initio, MD)

$$\frac{\partial C_\alpha(x, t)}{\partial t} = D_\alpha \frac{\partial^2 C_\alpha(x, t)}{\partial x^2} + \sum_{N}^{\beta, \gamma=1} S_\alpha(x, t)$$

$$\pm \sum_{N}^{\beta, \gamma=1} k_{\beta, \gamma}^2 D_\beta C_\beta(x, t)$$

$$\pm \sum_{\delta=1}^{N} \nu_\delta e^{-E_{A,\delta}/kT} C_\delta(x, t)$$

$$D = D_0 e^{-E_m/kT}$$

- source term: spectroscopy, MD, other
- energetics: ab initio, MD
- force fields: sink strength and reaction radii MD

3.3 Divertor fuel retention w/ ELMs

- PMI and fuel retention simulation with ELMy plasmas
  - input from $D_\alpha$ (or other method @ divertor)

![Graph showing D flux with ELMs and no ELMs phases]
3.c Divertor fuel retention w/ ELMs

PMI and fuel retention simulation with ELMy plasmas

- time $0 < t < 2.4 \text{ s}$
- limiter phase with no ELMs (~40 eV/D)

- D diffusion deep in the bulk
- no ELM-damage created
- D retained at natural impurities of W e.g. C, O

3.c Divertor fuel retention w/ ELMs

- PMI and fuel retention simulation with ELMy plasmas
- flat-top phase with ELMs
  - $f_{\text{ELM}} \approx 30 \text{ Hz}$
  - D retention in ELM-induced defects
- time $2.4 < t < 8 \text{ s}$
- divertor phase with ELMs ($f_{\text{ELM}} \approx 30 \text{ Hz}$; 4 keV/D)
- ELM-induced damage, D implantation

- D retained in near-surface ELM damage
- effect of target temperature
- complex dynamics of D trapping/detrappping and mobility of defects

3.c Divertor fuel retention w/ ELMs

- PMI and fuel retention simulation with ELMy plasmas
  - flat-top phase with ELMs
    - $f_{\text{ELM}} \sim 30$ Hz
    - D retention in ELM-induced defects

- time $2.4 < t < 8$ s
- divertor phase with ELMs ($f_{\text{ELM}} \sim 30$ Hz; 4 keV/D)

- D retained in near-surface ELM damage
- effect of target temperature
- complex dynamics of D trapping/detrapping and mobility of defects

$A + M \iff PSI \iff PMI$

Thank you!