Atomic and Molecular Spectroscopy in the Scrape-Off Layer of High Temperature Fusion Plasmas
Results from TEXTOR and JET

IAEA Spectroscopy Meeting Triest

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Magnetic Confinement: TEXTOR and JET Tokamks

Storage of Deuterium/Tritium in PFCs

Plasma-Facing Materials / Radiation Cooling

Scaling and „hidden parameters“
**Particle-Flux Determination**

- **Line emission**
  \[ \varepsilon = \frac{1}{4} n^2 \alpha \lambda \]
  \[ n_A = \sum_{\lambda} \lambda \sigma_{\lambda} \phi_{\lambda} \]
  \[ n_A = n_A \alpha < \sigma_{\lambda} > \]
  with \( B = A \sum_{\lambda} \lambda \sigma_{\lambda} \)

- **Particle flux**
  \[ \frac{d}{dt} < n_A > = -n_A \left( \frac{1}{\tau} \sigma_{\lambda} > \right) \]
  \[ \Gamma_A = \frac{4 \lambda}{B} \sum_{\lambda} \lambda \sigma_{\lambda} \phi_{\lambda} \]

Assumption of a fully ionising plasma & almost constant local plasma conditions in the region of emission. Improved ray: collisional rate model with rate coefficients.

**Regions of interest**

- **Scrape-off layer**
- **Core plasma**
- **Limiter**
- **Vessel walls**
- **FAR SOL:** \( N_e \sim 3 \times 10^{17} \text{m}^{-3}, 3 \times 10^{19} \text{m}^{-3} \)
- **T_e \sim 30-100 \text{eV}**
- **Divertor:** \( N_e \) up to \( 1 \times 10^{20} \text{m}^{-3} \), \( T_e \) down to \( 1 \text{eV} \)

**Plasma-Edge spectroscopy**

- **Passive spectroscopy:**
  - Determination of particle fluxes
  - Fuel recycling flux (e.g. D, H, D_2, HD, H_2)
  - Intrinsic impurity flux (C, W, Be, BeD, O, ...)
  - Extrinsic impurity flux (Ar, Ne, N, ...)
  - Energy and velocity distribution
  - Zeeman splitting analysis
  - Rovibrational population analysis of molecules
  - Doppler spectroscopy
  - Plasma parameter determination
  - Balmer-line ratios
  - Stark broadening
  - Line ratios
  - Penetration depths

- **Active spectroscopy:**
  - Local plasma parameters by e.g. He beams
  - Population of energetic levels by e.g. Laser-induced Fluorescence
  - Fuel content and impurity composition of layers by LIBS
  - Impurity content and plasma rotation in the edge e.g. CXRS

**Outline**

- **Introduction**
  - Plasma-Wall Interaction
  - JET tokamak
- **Spectroscopic techniques**
  - Hydrogen spectroscopy
  - Atoms and molecules
  - Recombining plasmas
- **Hydrocarbon spectroscopy**
  - Molecular break-up chain
  - Effective sputtering yields
  - Beryllium spectroscopy
  - Effective sputtering yields
  - Chemical-assisted physical sputtering
  - Tungsten spectroscopy
  - In-situ W calibration
  - Effective W sputtering yields
  - Summary

**Main visible transition of D_2 molecules**

- **Population of d level**
- **Visible spectral range:** electronic transitions with manifold of lines \( \sim 600\)
- 6 vibrational levels until dissociation reached
- CRM used for H vibration population simulation (similar to EIRENE)

**Fulcher-o band spectroscopy**

- **Fulcher-o band used for vibrational population, molecular flux and plasma conditions**
- In TEXTOR for \( n_d \) determination \( T_e \geq 30 \text{eV} \) / AUG for \( T_e \) determination I divertor \( (T_e < 10 \text{eV}) \)

**Rotational and vibrational population of D_2**

- **Determination of rotational population temperatures**
- **Determination of vibrational population temperatures**
- **Determination of the full emission of the electronic state**

**Plasma-Wall Interaction Facilities and spectroscopic observation systems**

- **Chemical-assisted physical sputtering**
- **Molecular break-up chain**
- **Recombining plasmas**
- **JET tokamak**
- **Plasma-Wall Interaction**
- **Physical sputtering**
- **Chemical-assisted physical sputtering**
- **Tungsten spectroscopy**
- **In-situ W calibration**
- **Effective W sputtering yields**

**Summary**

- **Beryllium spectroscopy**
- **Molecular break-up chain**
- **Recombining plasmas**
- **JET tokamak**
- **Plasma-Wall Interaction**
- **Physical sputtering**
- **Chemical-assisted physical sputtering**
- **Tungsten spectroscopy**
- **In-situ W calibration**
- **Effective W sputtering yields**

**Main visible transition of D_2 molecules**

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Deuterium atom to molecule ratio

- High ion flux to the wall, saturation and recycling
- Thermal release of D₂ from the (graphite) wall
- Molecular dissociation in the plasma via D₂⁺ providing one atom and one deuteron per D₂ molecules (at T_e >15 eV)

Deuterium dissociation channels

- Change of D₂ destruction mechanism of deuterium molecules at low T_e
  - Line width change of Doppler-broadened profile
- Destruction path via D⁺ only dominating above 15 eV
  - Destruction path via D₂ dissociating below 10 eV
  --results in two identical Franck-Condon atoms

Laser-induced Fluorescence of L₂

- Providing deuterium Ly-alpha radiation (3 stage LASER system)
- Probe of laser wavelength – Doppler-shifted fluorescence

JET: Divertor detachment and recombining plasma

- Balmer and Paschen series recombination measured (analysis with ADAS)
- Line ratio provides T_e, continuum jump analysis
- Stark broadening for n_e determination

JET: Tomographic reconstruction in detachment

How to measure in-situ an erosion yield?

- (hydrocarbon flux \( \Gamma_C \))
  - \( \Gamma_C \) = particle flux
  - \( \Gamma_C \) = accessible photon flux
  - \( \Gamma_C \) = carbon line (e.g. C II, C III)

Outlook

- Introduction
  - Plasma-Wall Interaction
    - JET tokamak
  - Spectroscopic techniques
    - Hydrogen spectroscopy
    - Hydrocarbon spectroscopy
    - Beryllium spectroscopy
    - Tungsten spectroscopy
    - Atomic and molecular diagnostics
    - Effective sputtering yields
    - Chemical-assisted physical sputtering
    - Effective W sputtering yields
    - Summary

Techniques used in JET to discriminate wall and divertor sources: B_t and T_e different
Dominant self-sputtering observed at high electron temperatures / impact energies

Local electron temperature determined by BeII line ratio (ADAS PECs)

Spectroscopy averages over observation spot (Tsurf, ion flux, geometry) and ERO code used for ITER Be wall lifetime predictions [D. Borodin PS2014].

Determination of Be sputtering yields in limited configuration to verify database

Total Be sputtering yield (eff.)

Be + e \rightarrow Be + D + e (75%)
With increase of Tsurf increasing release of BeD + e \rightarrow Be + D + 2e (25%)

Comparison of BeD A-X band, BeI and BeII at 528nm

BeII provides dissociation path

BeII at 528nm

TEXTOR: Carbon sputtering yield

Measurement of chemical and physical sputtering yield
Discrimination by surface temperature dependence of the yield

Transfer of techniques to different devices (JET/AUG) and plasma conditions

Effective Beryllium Sputtering Yields

BeD A-X spectrum at different Tsurf

Effective sputtering yields
Chemical-assisted physical sputtering

Be assisted physical sputtering of Be via BeDx

Chemical Assisted Physical Sputtering of Be via BeDx

Comparison of BeD A-X band, BeI and BeII provided dissociation path
Dominant Be + e \rightarrow Be + D + e (75%) over BeD + e \rightarrow Be + D + 2e (25%)
With increase of Tsurf increasing release of D \rightarrow less D in stored in Be!

BeII at 528nm

TEXTOR W limiter

JET W divertor
**Effectice S/XB for different WI lines**

- Modelling: ADAS/Mons data (O'Mullane/Palmer et al.)
- Experiment: TEXTOR data (Brezinsek/Laengner)

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**JET: ELM-induced W sputtering**

- H-mode plasmas have energetic transients (ELMs) which hit the target at impact energies of 10eV or above
- Residual W in seeded plasmas determined by ELMs (Be+N+D impact) (Reference: [PPCF])

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**JET: D2 Release from W Divertor**

- Contribution of reflected ions (neutralised at the PFC) is larger for W than for C PFCs
- Non-Boltzmann population in the vibrational ground state measured – different population to previous JET-C measurements. Detailed analysis started.

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**Summary**

(i) Material selection has vital impact on the tokamak plasma

Tokamak plasma has vital impact on the plasma-facing materials

(ii) Decoupling causes misinterpretation of plasma properties

(iii) Spectroscopy in the plasma edge (near and far SOL) is a useful tool to characterise in-situ interaction processes and helps to validate tools for ITER (and other plasmas)

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**Effective Tungsten Sputtering Yields**

- General W sputtering well described by Be ions / slight shift in energetic threshold
- Plasma cooling by N2/Ar seeding till E_d drops below threshold (Reference: [JMN 2013/2014])

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**Plasma cooling leads to reduction of the W source down to physical sputtering threshold**

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**Rotational population temperature**

- Rotational population temperature depends on gas temperature
- Rotational population temperature depends on T_e
- At known surface temperature => rotational temperature useful for T_e measurement

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**JET: Inner divertor remains W source**

Inner divertor target plate at the strike line is not a net deposition zone for Be!

Not enough Be from the main chamber into the divertor => balance shifted to erosion in contrast to JET-C and C with 50µm thick layers!

Impurities: C, N, O at lower vertical tiles
Grotian Diagramm for Neutral W

- Level diagram and ground state structure

NIST table

- Selection of most prominent transitions visible in the edge plasma

Hydrocarbon injection for in-situ quantification

- Hydrocarbon catabolism: dissociation chain depends on plasma parameter

In-situ calibration: Hydrocarbon injection for quantification

- In-situ calibration with a known source of hydrocarbons
- C_2D_4 injected and CD A-X or C_2 d-a band observed
- Intermediate radicals can’t be observed by spectroscopy in the UV-NIR range

JET: Chemical erosion of C in cold plasmas

- L-mode density ramp: reduction of carbon fluxes at high ion flux and low T_e

- L-mode feedback-controlled discharge with detached outer divertor
- L-mode: Intrinsic carbon source
- Reduces with increasing ion flux
- L-mode: Extrinsic carbon source observable!
- L-mode: Intrinsic carbon source strongly reduced at T_e<2 eV.

- In-situ calibration with a known source of hydrocarbons
- C_2D_4 injected and CD A-X or C_2 d-a band observed
- Intermediate radicals can’t be observed by spectroscopy in the UV-NIR range