Emission spectroscopy applied to divertor plasmas of magnetic fusion devices

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Magnetic fusion: backgrounds

• Chemical reactions
  \[ \text{H}_2^+ + (1/2) \text{O}_2 \rightarrow \text{H}_2 \text{O}^+ + 2.96 \text{ eV} \]

• Fusion reactions (nuclei)
  \[ \text{T} + \text{D} \rightarrow \text{He}^4 + n + 17.6 \text{MeV} \]

Recipes: create a plasma, confine it (with powerful magnetic fields) and heat it.

\[ \text{Lawson criterion}: n_e T_e > 10^{21} \text{ (keV m}^{-3} \text{ s)}, \ T_e \approx 10^{-20} \text{ keV}. \]

Core:

\[ \text{T}_e \approx 10 \text{ keV} \]
\[ n_e \approx 1 \times 10^{20} \text{ m}^{-3} \]

Divertor:

\[ \text{T}_e \approx 0.2 - 100 \text{ eV} \]
\[ n_e \approx (0.1 - 50) \times 10^{19} \text{ m}^{-3} \]

Role of the divertor

• Control of fuel particles
• Control of impurities
• Mitigation of heat load onto target plates

\[ \text{Detached plasma} \rightarrow \text{Radiation} \]

Radiation

• protects PFC
• used for diagnostics

Generalities on emission line shapes

\[ \frac{d \Phi}{d \omega} = \frac{a^4}{2 \pi \omega^2} \sum_{m,n} \delta(\omega - \omega_{mn}) \left| \langle m | \mathbf{x} | n \rangle \right|^2 \rho_{mn} \]

\[ \omega_{mn} = \mathbf{E}_m - \mathbf{E}_n \]

• Assuming \( a^4 \) to be a constant factor, one gets the line shape profile:

\[ I(\omega) = \sum_{m,n} \delta(\omega - \omega_{mn}) \left| \langle m | \mathbf{x} | n \rangle \right|^2 \rho_{mn} \]

• Using Fourier Transform, one obtains the dipole autocorrelation function:

\[ C_{\omega}(t) = \int e^{i\omega t} I(\omega) d\omega = \sum_{m,n} e^{i\omega_{mn} t} \left| \langle m | \mathbf{x} | n \rangle \right|^2 \rho_{mn} \]

Modeling of emission line shapes in plasmas

• Spectral line profile = the inverse Fourier transform of \( C_{\omega}(t) \):

\[ I(\omega) = \frac{1}{\pi} \text{Re} \int e^{i\omega t} C_{\omega}(t) dt \]

\[ C_{\omega}(t) = \text{Tr} \left[ \hat{\mathbf{X}}(t) \hat{\mathbf{X}}^\dagger(0) \right] \]

Requirements:

• Solve Schrödinger equation for the emitter with the Hamiltonian

\[ \hat{H} = \hat{H}_0 + \hat{H}_I - \mu(\mathbf{E} + 2\hat{\mathbf{B}}) \cdot \hat{\mathbf{A}} \]

• Atomic physics data: dipole matrix elements, level energies
• Density matrix \( \rho \): statistical equilibrium or using collisional radiative models

Tools used to analyze observed spectra

Standard model of Stark broadening

• Different timescales for ions and electrons \( \Rightarrow \) separation of their interactions with the emitter:
  - Collisional approach (impact approximation) for electrons \( \Rightarrow \) homogeneous broadening \( \Rightarrow \) Lorentzian with FWHM = \( \Delta n_T \): line centre
  - Statistical approach (quasi-static approximation) for ions \( \Rightarrow \) inhomogeneous broadening: line wings

• Several models/codes exist:
  - PPP code based on the FFM, MMM, ...

See Griem’s books for details:
- Plasma spectroscopy (1964)
- Spectral line broadening by plasmas (1974)
- Principles of Plasma spectroscopy (1997)

Outline

1. Modeling and analysis of the D\text{\textalpha} line
2. Modeling and analysis of the hydrogen Balmer series
3. Spectroscopy of carbon impurities
4. Spectroscopy of pellet ablation clouds injected in LHD
5. Conclusions

1. Attached plasmas: D\text{\textalpha} line emission in Tore-Supra

- H\text{\textalpha}/D\text{\textalpha} line spectra:
  - measured // B-field
  - governed by Doppler broadening and Zeeman effect

2. Detached plasmas: High-\(n\) Balmer lines

- Theoretical Balmer series limit:
  \[ \lambda_{\text{lim}} \approx 3646 \text{ Å} \]
- Balmer lines merge into the continuum
  \( \lambda_{\text{lim}} \approx 3680 \text{ Å} \)
- Inglis-Teller formula:
  \[ n_{\text{lim}} = \left( \frac{2}{3} \right)^{3/2} \left( \frac{1}{n_{\text{lim}} + 1 \text{ Å}} \right)^{3/2} \]
  \( n_{\text{lim}} = 9.3 \times 10^{10} \text{ m}^{-3} \)

Whole spectral fitting provides temperatures and more accurate densities

Synthetizing whole Balmer spectra/comparing to measurements

Analytic continuity model for the smooth line merging into the continuum

- \( n_i = 9 \times 10^{19} \text{ m}^{-3}, T_i = 0.75 \text{ eV} \)

Extension to neutral helium diffuse series

In a helium discharge with strong D\text{\textalpha} puffing, transitions from highly excited levels have been observed in the JET divertor.
3. Spectroscopy of carbon impurities from JT-60U

Schematic view of the measurements in JT-60U

High-resolution C IV n=6-7 spectra (S4-S11) correspond to odd viewing chords 19-33 of the large-band visible spectrometer

**MARFE: Multifaceted Asymmetric Radiation From the Edge**

**Fitting C IV n=6-7 line spectra measured in JT-60U**

Example of a spectrum along the most peripheral viewing chord (S11, chord 33)

* sensitivity to Stark broadening
* All spectra were measured using a linear polarizer allowing the transmission of the $\sigma$ component.
* Profiles calculated with PPP for $B=0$, retaining Stark-Doppler broadening

A good agreement for: $N_e=1.2 \pm 0.2 \times 10^{20}$ m$^{-3}$, $T_e=T_i=10.0$ eV

**Spatial distribution of the electron density**

Accurate distributions of electron density and temperature used for the evaluation of power balance calculations

Typical large-band spectral measurements and temperature determination

* Radiation dominated by C II and C III line emissions: C$^+$/C$^{2+}$ ions.
* Use of Boltzmann plot to obtain the electron temperature

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4. Spectroscopy of ablation clouds of pellets in LHD

**Spectroscopy of pellet ablation clouds**

* Deuterium pellet injection an efficient technique for:
  - Plasma fuelling
  - Plasma control (ELMs mitigation, ELM pacing)
* Other material pellets (C, Al, Ti, ...) injected for:
  - Recycling studies
  - Impurity transport studies

**High-/very high-resolution spectroscopic measurements**

Spectra of the C II 723-nm line: transition $[1s^22s^2] \, ^1P_1 - 3d \, ^1D_2$

Fitting (analysis) of such spectra gives $n_e$
Fitting of high-resolution spectra with the deconvolution technique

- Method: Knowing the gaussian contribution (Doppler, Zeeman, instrum. function), the lorentzian Stark contribution is deduced from the measured profile. Then, from the Stark FWHM, the electron density is obtained from the graph of measured FWHM vs ne.


Fitting the very highly resolved spectra: as a challenge case for the 2nd SLP (Vienna, August 2013)

- Atomic structure in presence of magnetic field (B=2 T):
  - Zeeman splitting of the order of the fine structure splitting for the upper level intermediate fields
- Line broadening mechanisms:
  - Stark (electron contribution dominant), Zeeman and Doppler.
  - Use of the PPP and PPP-B codes


Multi-code fitting of the C II 723-nm component

- Dispersion of the results (for the fitting no constraints on the angle of observation, B-field, density....)
- PPP-B calculations in the framework of weak-field approximation
  - Full treatment of the zeeman effect on the atomic structure outside of the line shape code PPP (A. Conrad M2 training: 2014)

M. Koubbi et al, Atoms 2014, 2(3), 319-333

Latest tentative fitting of the C II 723-nm π and σ components

Fit better but still to be improved
Radiation absorption not included

What else? It will be very interesting to link the ablation cloud parameters to the host plasma, to the ablation models and to search for any spectroscopic signature of a collective motion of the cloud

Conclusions

- Passive spectroscopy is still important for magnetic fusion

- Several applications:
  - Attached plasmas (Tore-Supra): De spectra useful for particle flux calculations (particle balance, retention...)
  - Detached plasmas (JET): the most promising scenarios to mitigate power and particle loads on the targets (High-n Balmer emission determination of the divertor plasma parameters
  - Spectroscopy of carbon impurities for JT-60U and LHD: characterization of the divertor plasma and the ablation cloud of injected pellets