Emission spectroscopy applied to divertor plasmas of magnetic fusion devices

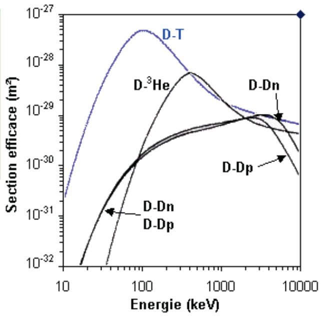
M. Koubiti[1], M. Goto[2], T. Nakano[3]

[1]PIIM UMR 7345 Aix-Marseille Université-CNRS, Marseille F-13397, France
[2]National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan
[3]Japan Atomic Energy Agency, 801-1, Mukoyama, Naka 311-0193, Japan

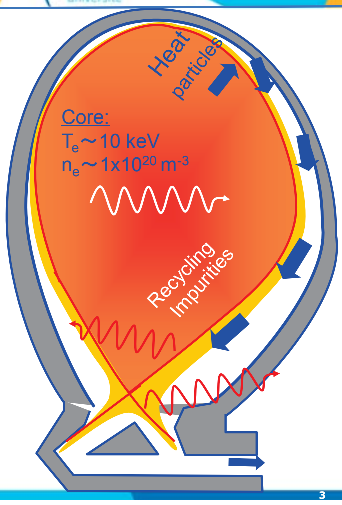
Magnetic fusion: backgrounds

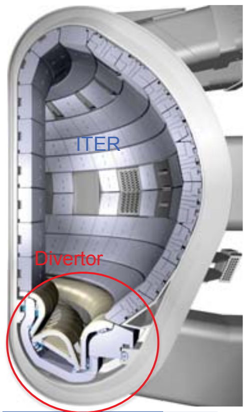
- Chemical reactions
$H_2+(1/2)O_2 \rightarrow H_2O+2.96$ eV

- Fusion reactions (nuclei)
T+D→He⁴+n + 17.6MeV

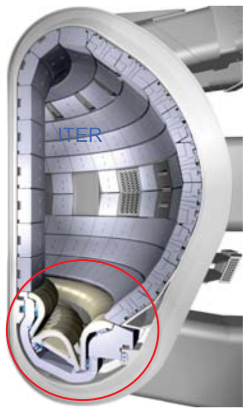


- Recipes: create a plasma, confine it (with powerful magnetic fields) and heat it.
  - ➔ Lawson criterion: $n_e\, T_e\, \tau_E > 10^{21}$ (keV m^{-3} s), $T_e \approx 10\text{-}20$ keV.





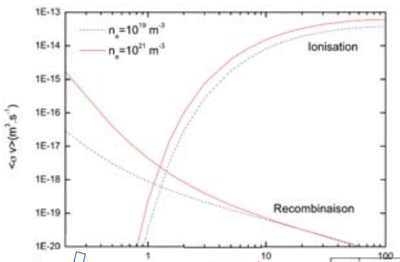
Divertor: $T_e \sim 0.2\text{-}100$ eV
$n_e \sim (0.1\text{-}50)\text{x}10^{19}$ m^{-3}

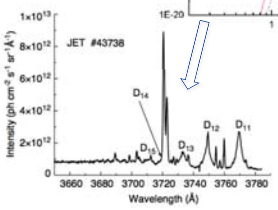


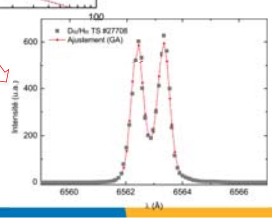
Role of the divertor
- Control of fuel particles
- Control of impurities
- Mitigation of heat load onto target plates
  - <= Detached plasma
  - => Radiation

Radiation
- protects PFC
- used for diagnostics

Divertor plasma conditions determine which D lines can be observed





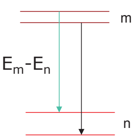


Generalities on emission line shapes

- Power emitted by a quantum-mechanical system:

$$\frac{dP}{d\omega} = \frac{\omega^4}{3\pi\varepsilon_0 c^3} \sum_{n,m,i} \delta(\omega-\omega_{mn}) \left|\langle n|e\,x_i|m\rangle\right|^2 \rho_m$$

final state — initial state



- Assuming ω^4 to be a constant factor, one gets the line shape profile:

$$I(\omega) = \sum_{n,m,i} \delta(\omega-\omega_{mn}) \left|\langle n|e\,x_i|m\rangle\right|^2 \rho_m$$

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

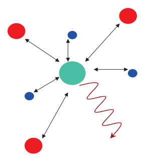
$$C_{dd}(t) = \int_{-\infty}^{+\infty} e^{i\omega t} I(\omega)\, d\omega = \sum_{n,m,i} e^{i\omega_{mn} t} \left|\langle n|e\,x_i|m\rangle\right|^2 \rho_m$$

Modeling of emission line shapes in plasmas

- Spectral line profile=the inverse Fourier transform of $C_{dd}(t)$:

$$I(\omega) = \frac{1}{\pi} \Re e \int_0^{\infty} e^{-i\omega t} C_{dd}(t)\, dt$$

$$C_{dd}(t) = Tr\{\vec{D}(0)\vec{D}(t)\rho\}_{av}$$



- Requirements:
  - Solve Schrödinger equation for the emitter with the Hamiltonian

$$H = H_0 + H_{FS} - \mu_B(\vec{L}+2\vec{S}).\vec{B} - \vec{d}.\vec{F}(t)$$

Zeeman — Stark

  - Atomic physics data: dipole matrix elements, level energies
  - Density matrix ρ: statistical equilibrium or using collisional radiative models

Standard model of Stark broadening

- Different timescales for ions and electrons ⇒ separation of their interactions with the emitter:
  - Collisional approach (impact approximation) for electrons ⇒ homogeneous broadening ⇒ Lorentzian with FWHM=f(n_e, T_e): line centre
  - Statistical approach (quasi-static approximation) for ions ⇒ 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)

*-B. Talin et al, Phys. Rev. A **51**, 1918 (1995) ;*
-A. Calisti et al. Phys. Rev. E 81, 016406 (2010).
*-C. Stehlé, R. Hutcheon, Atsron. Astrophys. Suppl. Ser. **140**, 93 (1999).*

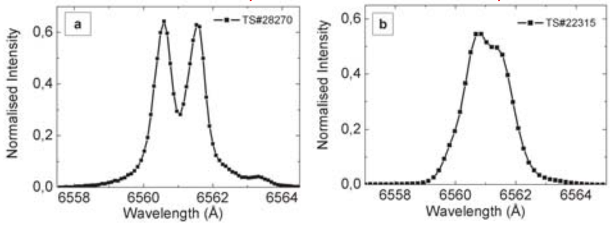
Outline

1. Modeling and analysis of the Dα 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: Dα line emission in Tore-Supra

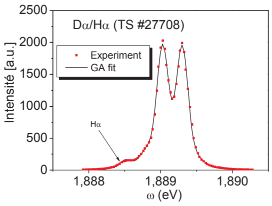
- Hα/Dα line spectra:
  - measured // B-field
  - governed by Doppler broadening and Zeeman effect

Almost all the time: symmetric — few cases: asymmetric



Fitting of symmetric Dα spectra

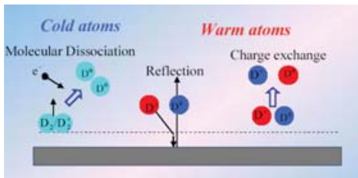
- Two neutral populations:
  - a warm neutral population resulting from CX reactions (T=10-20 eV)
  - A cold neutral population resulting from molecular dissociations (T=1-3 eV)



Recycling mechanisms: chemical and physical sputtering

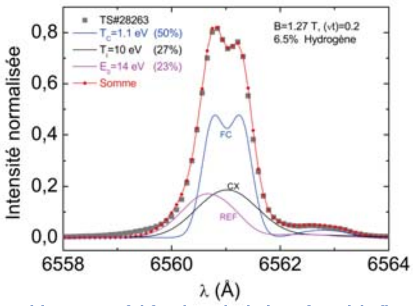
Asymmetric Dα spectra

- Three neutral populations:
  - Warm (CX)
  - Cold (molecular dissociation)
  - A third neutral population termed "refleted atoms" resulting from a reflection process. These neutrals undergo a partial thermalization process through elastic collisions with the plasma ions modeled using a Fokker-Planck equation.



M. Koubiti et al, Plasma Phys. Control. Fusion **44** *(2002)* 261.

Fitting of an asymmetric Dα spectrum



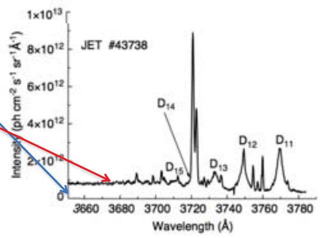
- **These quantities are useful for the calculation of particle fluxes**

➔ **This work was followed by studies of line wings, effect of fluctuations and turbulence on line spectra.**

Y. Marandet et al, High Energy Density Physics **5**, *312 (2009)*

2. Detached plasmas: High-n Balmer lines

- Theoretical Balmer series limit: λ^B_{lim}≈3646 Å
- Balmer lines merge into the continuum @ λ_c≈3680 Å.



- Inglis-Teller formula: $n_e^{max.}$

$$n_e^{max} = \frac{Z^{9/2}}{120\, a_0\, Z_p^{3/2}} \left[\frac{1}{n_m^2} - \frac{1}{(n_m+1)^2}\right]^{3/2} (n_m^2-4)^{-3/2},$$

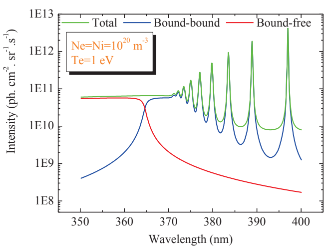
m=15 ➔ n_e=9.5x10^{19} m^{-3}

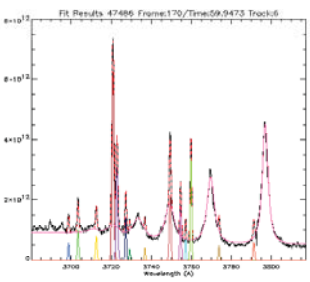
Whole spectral fitting provides temperatures and more accurate densities

Synthetizing whole Balmer spectra/comparing to measurements

Analytic continuity model for the smooth line merging into the continuum

n_e=9x10^{19} m^{-3}, T_e=0.75 eV

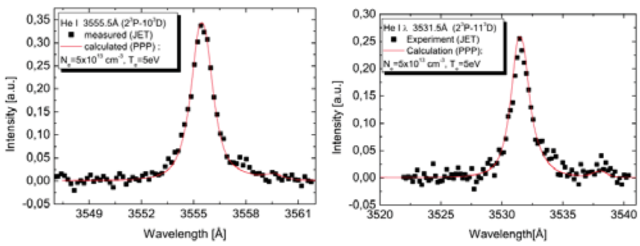




S. Loch, PhD Thesis 2001,University of Strathclyde, UK
M. Koubiti *et al*, JQSRT **81** 265-273 (2003)

Extension to neutral helium diffuse series

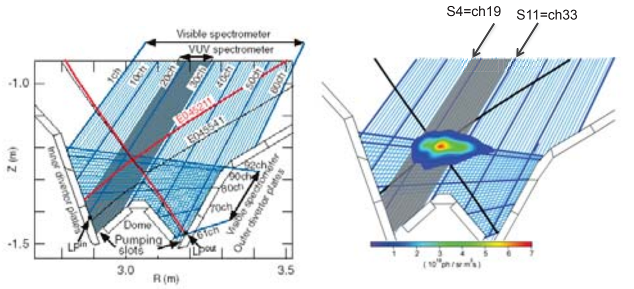
In a helium discharge with strong D_2 puffing, transitions from highly excited levels have been observed in the JET divertor



M. Koubiti et al, Contrib. Plasma Phys. **46**, 661 (2006)

3. Spectroscopy of carbon impurities from JT-60U

Schematic view of the measurements in JT-60U

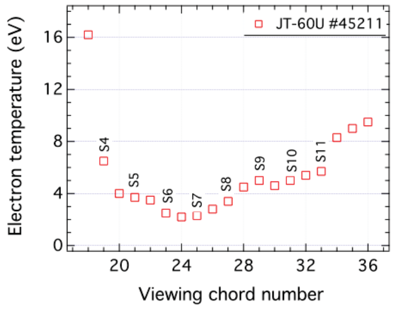


High-resolution C IV n=6-7 spectra (S4-S11) correspond to odd viewing chords 19-33 of the large-band visible spectrometer

MARFE: Multifaceted Asymmetric Radiation From the Edge)

Spatial distribution of the electron temperature T_e

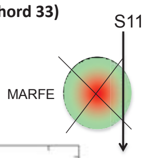
Line intensity ratio technique applied to C IV lines (Levels p=7 and p=9)



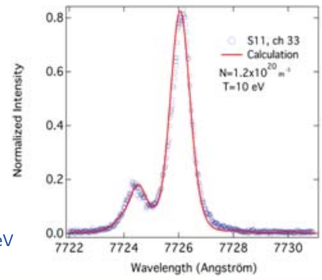
➔ T_e values used as input in the PPP code for the calculation of C IV n=6-7 line profiles

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)



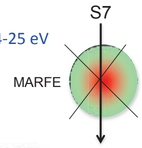
- sensitivity to Stark broadening
- All spectra were measured using a linear polarizer allowing the transmission of the π component.
- Profiles calculated with PPP for B=0, retaining Stark-Doppler broadening

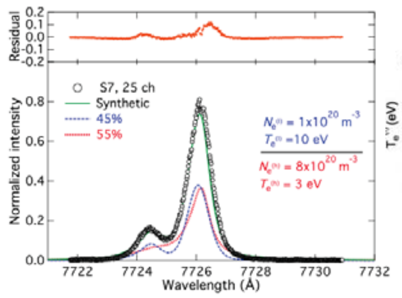


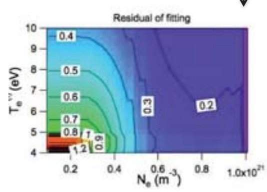
A good agreement for:
$N_e=1.2\pm0.2\times10^{20}\ m^{-3}$, $T_e=T_i=10.0$ eV

A two-layer plasma model to fit spectra along central viewing chords w.t. MARFE* centre

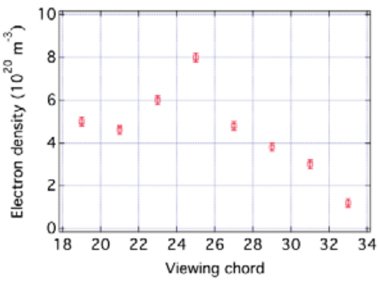
- Low density layer: $N_e^{(l)}=10^{20}\ m^{-3}$ fixed, search for $T_e^{(l)}=T_i^{(l)}$ in the range 4-25 eV
- High density layer: $T^{(h)}$ fixed , search for $N_e^{(h)}$ in the range 10^{20}-$12^{21}\ m^{-3}$







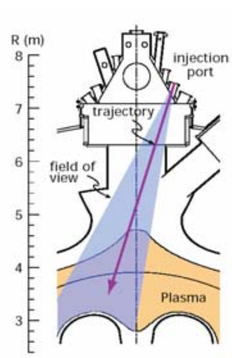
Spatial distribution of the electron density



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

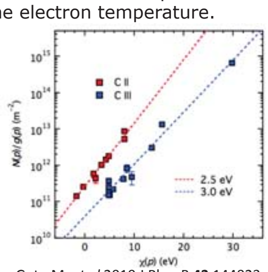
4. Spectroscopy of ablation clouds of pellets in LHD

- 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



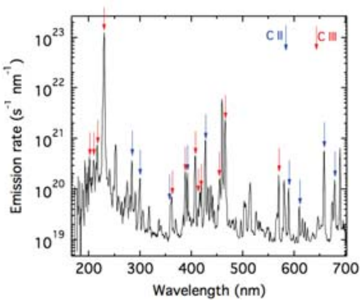
Typical large-band spectral measurements and temperature determination

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



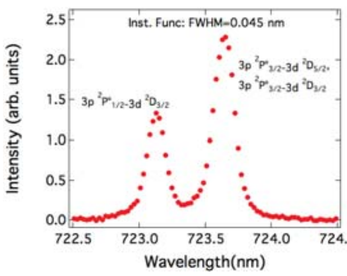
Goto M. *et al* 2010 J Phys B **43** 144023

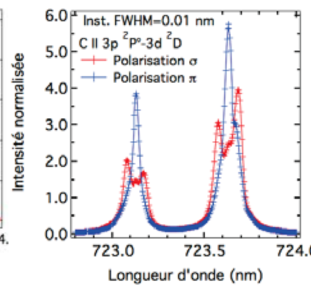
Instrumental function FWHM=1.5 nm



High-/very high-resolution spectroscopic measurements

Spectra of the C II 723-nm line: transition $[1s^22s^2]\ 3p\ (^2P^\circ)$ – $3d\ (^2D)$

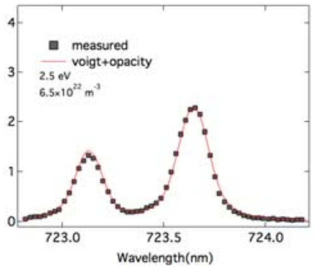




Fitting (analysis) of such spectra gives n_e

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 n_e.



Goto M. *et al* 2010 J Phys B **43** 144023

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

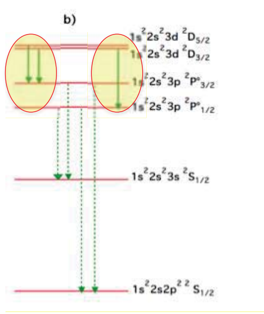
- **Atomic structure in presence of magnetic field (B=2 T):**

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.

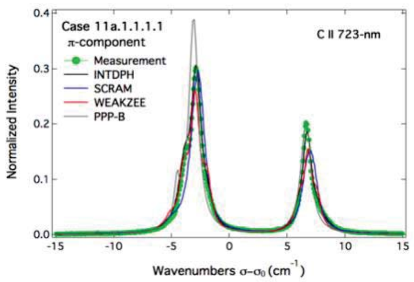
Convolution of Stark-Zeeman profiles with gaussians (Doppler effect + instrumental function)

- Use of the PPP and PPP-B codes



A. Calisti et al, *Phys. Rev. E* 2010, 81, 016406.
S. Ferri et al, *Phys. Rev. E* 2011, *84*, 026407.

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

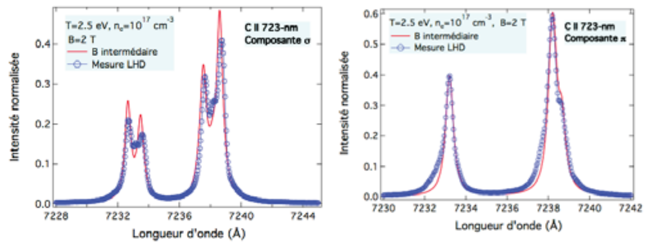


- Dispersion of the results (for the fitting no constraints on the angle of observation, B-field, density….)
- PPP-B calculations in the framework of weak-field approximation

➔ Full treatment of the zeeman effect on the atomic structure outside of the line shape code PPP (A. Conrad M2 training: 2014)

M. Koubiti 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): Dα 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