Line broadening and spectroscopic analysis of light elements

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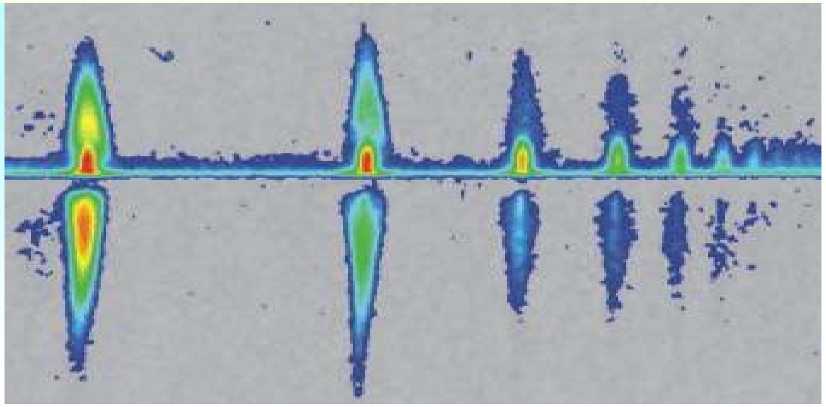
Line shapes for a plasma diagnostic

-Intensity

-Broadening : Doppler, Stark

-Zeeman splitting

Analysis results in the knowledge of plasma parameters, bulk motion, turbulence..

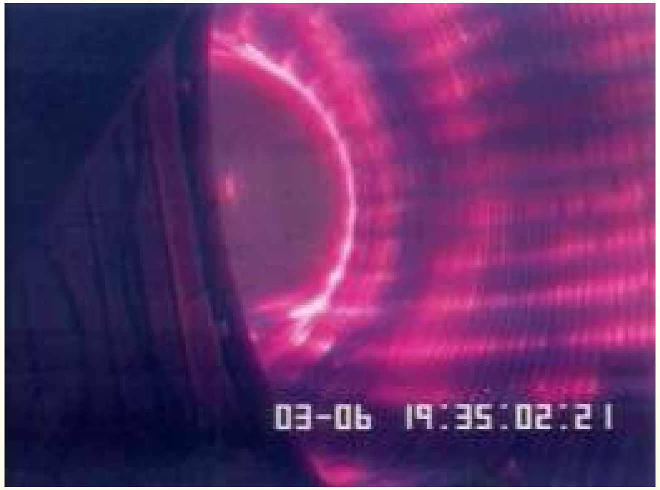


H and He –like Al spectra

Laser plasma

OUTLINE

1. Modelling of line shapes
2. Hydrogen isotopes in the edge plasma
3. Stark effect
4. Effect of hydrodynamic turbulence



Tore-Supra

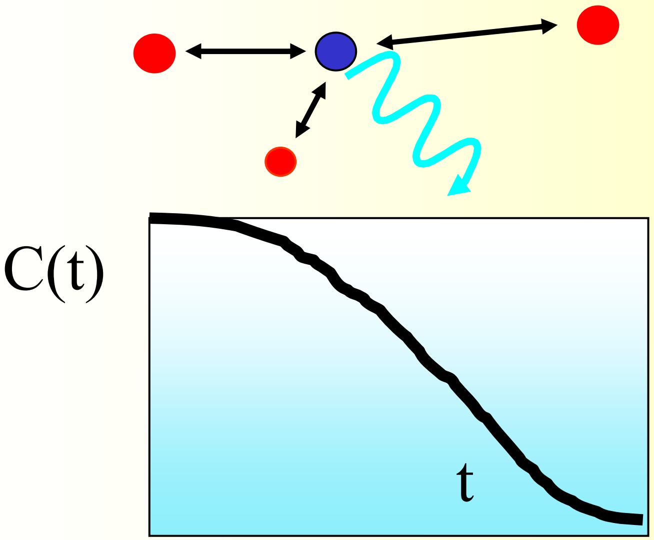
Modelling of line shapes

The spectral lineshape is obtained from a Fourier transform of the emitters dipole autocorrelation function C(t)

$$L(\omega)=\frac{1}{\pi}\mathrm{Re}\int_0^{\infty} e^{i\omega t}C(t)\,dt$$

Time of interest : $t_i \sim 1/\Delta\omega_{1/2}$

$$C(t)=\mathrm{Tr}\left\{\rho\vec{D}(0)\vec{D}(t)\right\}_{av}$$



Requirements :

- Solution of the emitters Schrödinger equation with the Hamiltonian :

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

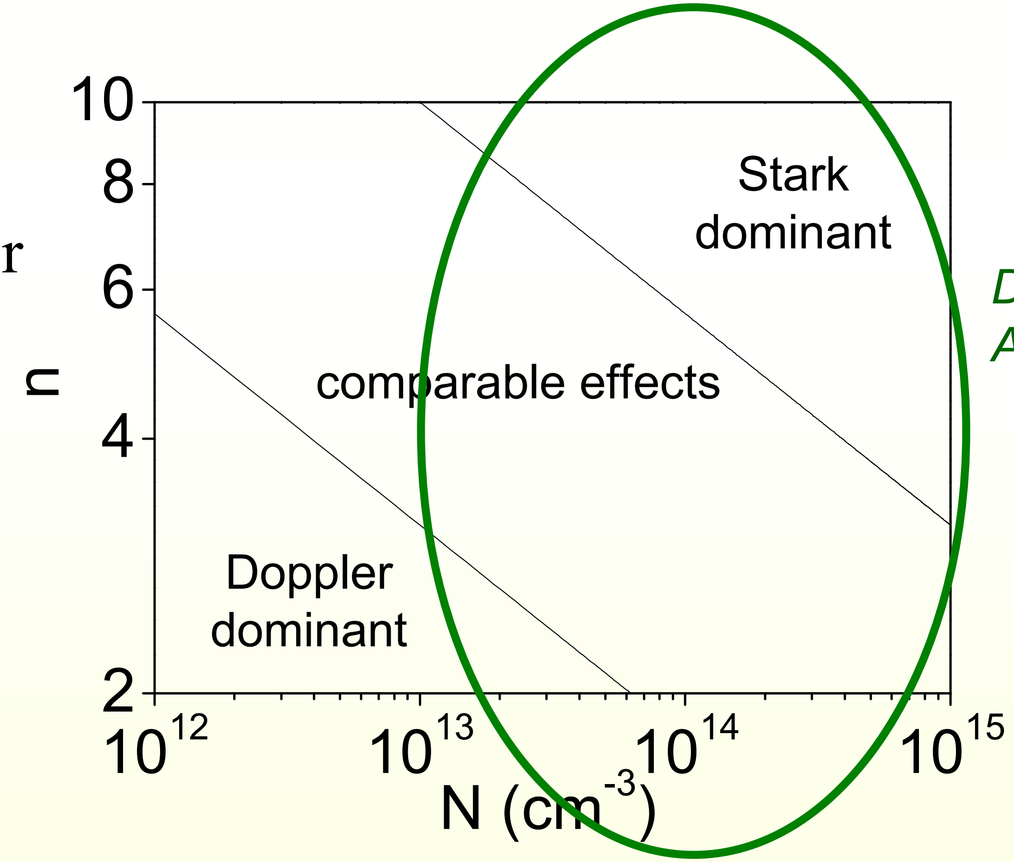
- Atomic physics data : dipoles, atomic levels
- Density matrix ρ : collisionnal-radiative model

Comparison of Doppler and Stark broadening

hydrogen in a tokamak edge plasma

T = 1 eV
Lyman lines(n -> 1)

Principal
quantum number



Divertor plasma
Alcator, ITER, …

Neutral populations from Doppler line shapes

- Different populations of neutrals coexist in the edge plasma :

Cold atoms from molecular dissociation

Warm atoms from reflexion and charge exchange

Using a Genetic Algorithm (GA), it is possible to obtain the population fractions and the plasma parameters

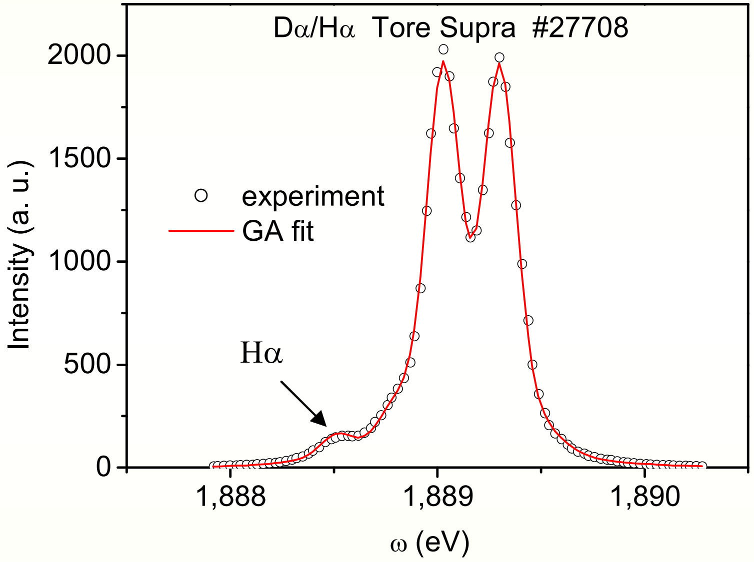
GAs are search and optimization algorithms based on the analogy to the mechanics of natural selection

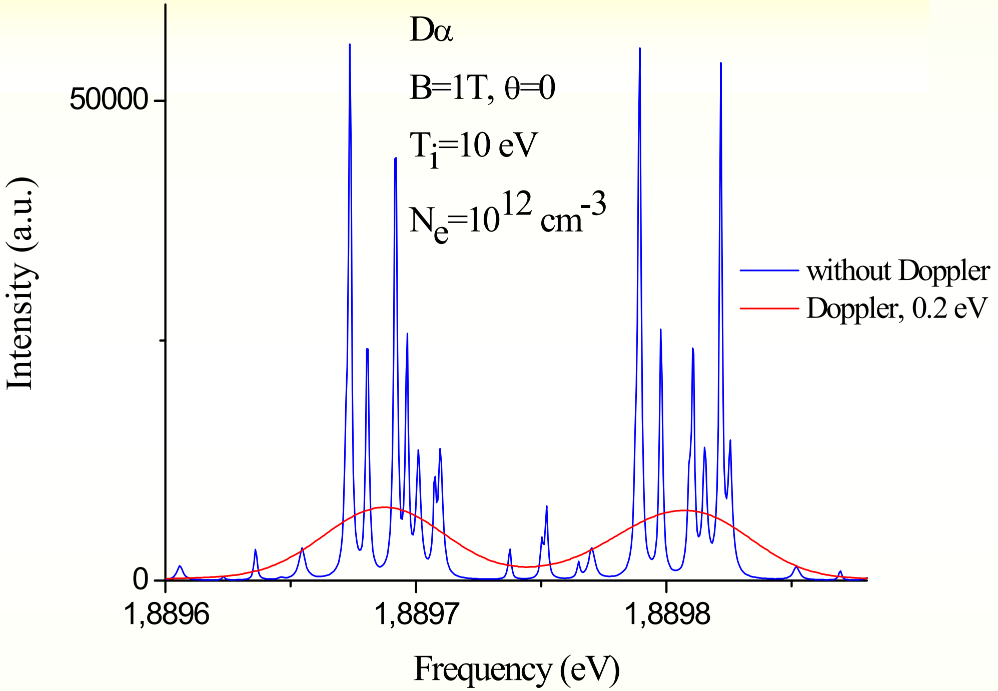
GAs algorithms are reliable, robust and fast

Broadening mechanisms on the Balmer α

On most present tokamaks, broadening of Dα is dominated by Doppler broadening and Zeeman effect

Neutral temperature measure





53 % molecular dissociation

2.5 eV or less (0.2 eV observed TEXTOR)

32 % Charge exchange 17 eV

\+ 8% 130 eV

7% H

For high resolution spectroscopy, modeling of Dα should take into account fine structure, Zeeman and Stark effect

Stark broadening (hydrogen)

Dominant for high principal quantum number n, and/or high densities

Two limiting models: collision time ($\tau_c \sim d/v$) compared to the time of interest t_i

Impact : $\tau_c << t_i$

$C(t)=e^{-\phi t}$

Static $\tau_c >> t_i$: $E(t=0)$

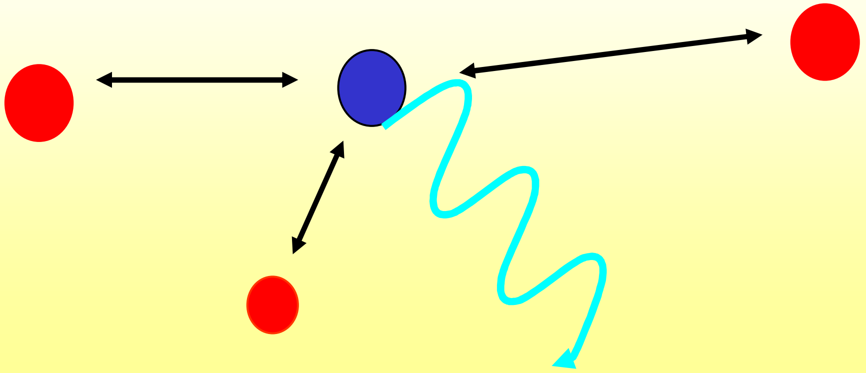
$C(t)=\{e^{-(i/\hbar)\mathbf{D}.\mathbf{E}\,t}\}_{av}$

intermediate conditions for

-Ion perturbers for low n lines, high plasma density (Alcator, ITER…)

-Electrons with high n lines, high plasma density

Dynamic many body problem



Benchmark profiles by simulation

-The electric field $\vec{E}(t) = \vec{E}_e(t) + \vec{E}_i(t)$ is simulated

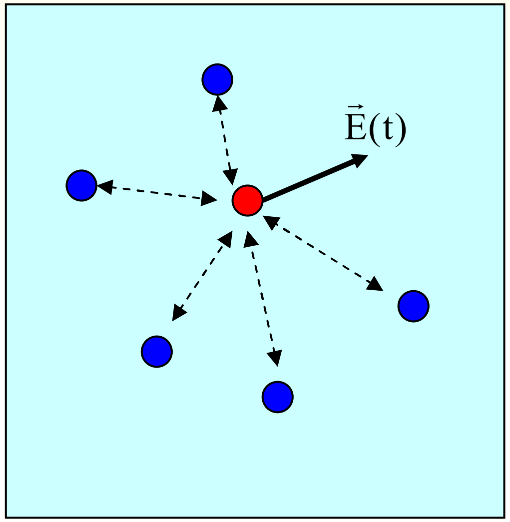
-The Schrödinger equation is solved numerically

$$i\hbar \frac{dU(t)}{dt} = [H_0 - \vec{D}.\vec{E}(t)]U(t)$$

U(t) is the time evolution operator of the emitter

No assumption on the dynamics

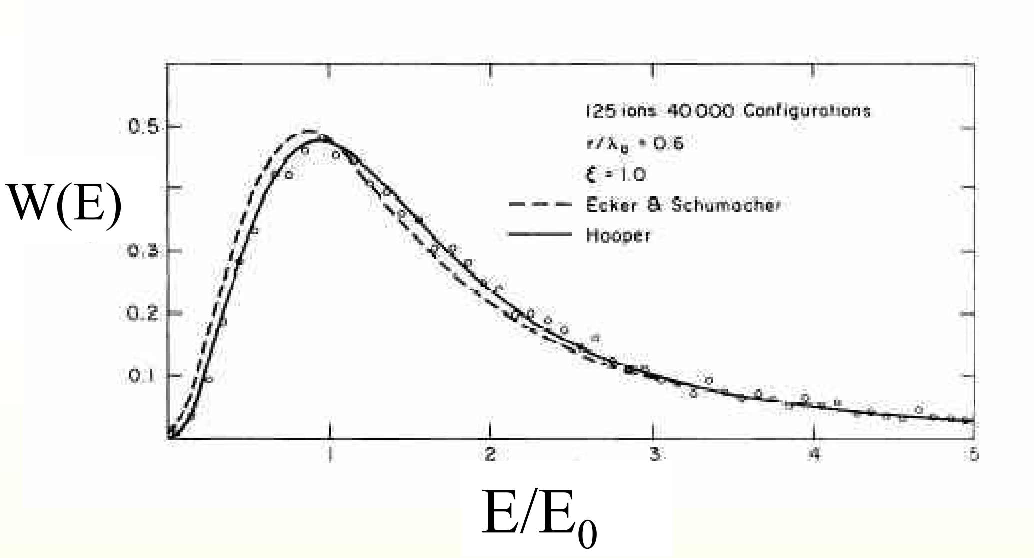
Accurate, but computer time may be prohibitive for complex atoms/ions



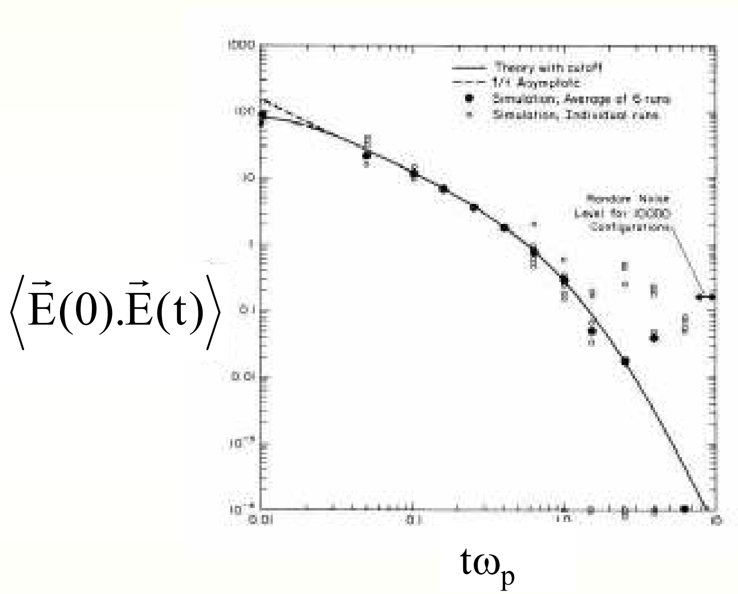
A line shape code using statistical properties of the microfield E: PPP

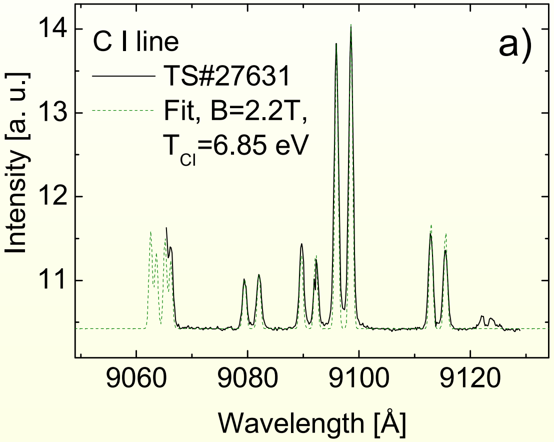
Based on the "frequency fluctuation model" which uses 2 properties of E:

-The static microfield distribution W(E)



-The electric field correlation function

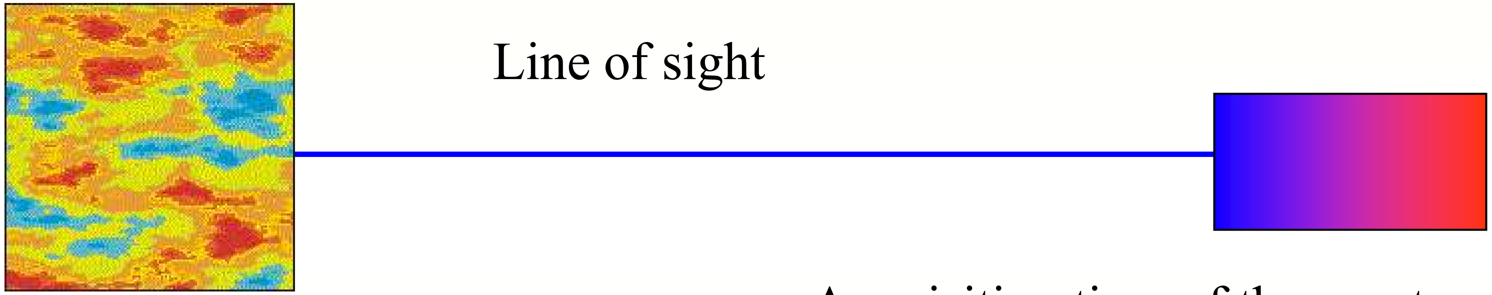




PPP accepts data for an arbitrary atom/ion

Line shape and hydrodynamic turbulence

In low frequency drift wave turbulence, the fluctuation rate may rise up to several tens of percent (n,T,u)



Line of sight

Acquisition time of the spectrometer : τ_m

Turbulence fluctuation time : τ_{turb} ~10 μs
Turbulence length scale : 10 ρ_i ~ cm

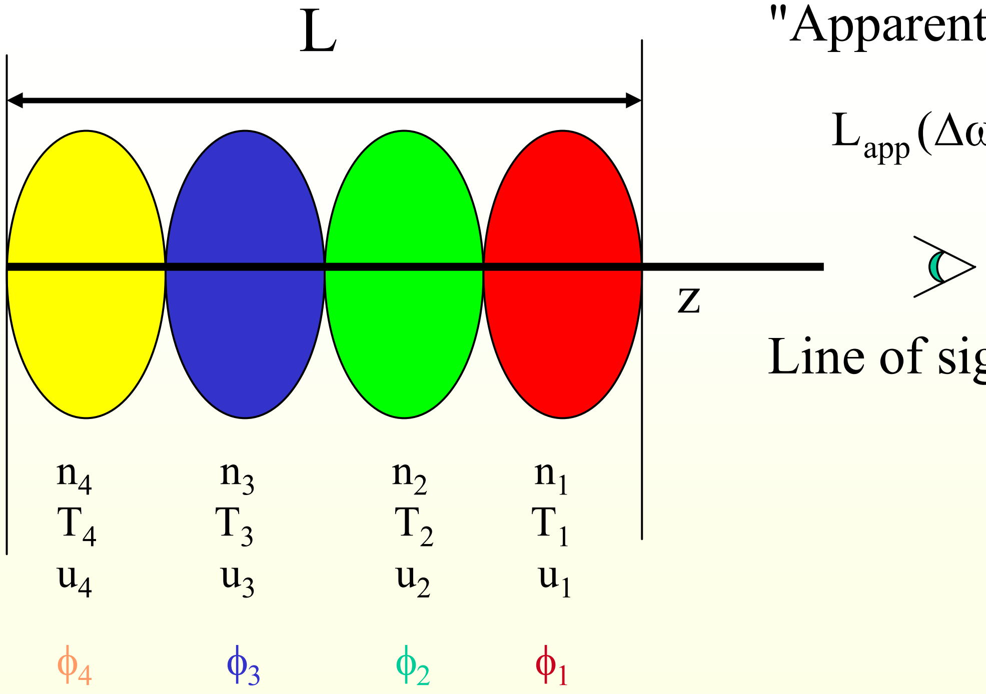
Usually $\tau_m >> \tau_{turb}$, and the time of interest for the line shape $<< \tau_{turb}$

May the profile be affected by hydro turbulence?

The turbulent fluctuation is static for the emitter

But since the acquisition time is large compared to the turbulent fluctuations,

a measure along a line of sight performs a time and spatial average



"Apparent profile"

$$L_{app}(\Delta\omega) = \frac{1}{\tau_m}\int_0^{\tau_m}\frac{1}{L}\int_0^L B(z,t)\, L(\Delta\omega, z, t)\, dz\, dt$$

A statistical approach

The observed profile may be expressed with the help of a Probability Density Function (PDF) W of the fluid variables ϕ

$$\boxed{L_{app}(\Delta\omega) = \int W(\phi)B(\phi)L(\Delta\omega,\phi)d\phi}$$

PDF of the fluid variable

Brightness of the line (collisionnal-radiative model)

Line shape model

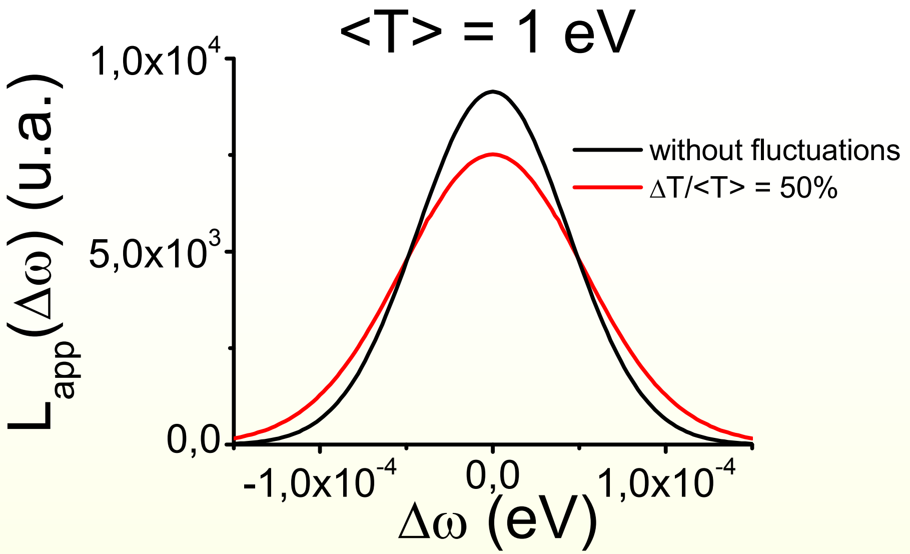
Y. Marandet et *al.*, Eur. Phys. J. D. 39, 247(2006)

Apparent profile : <T> dependance

Full Hα line calculation

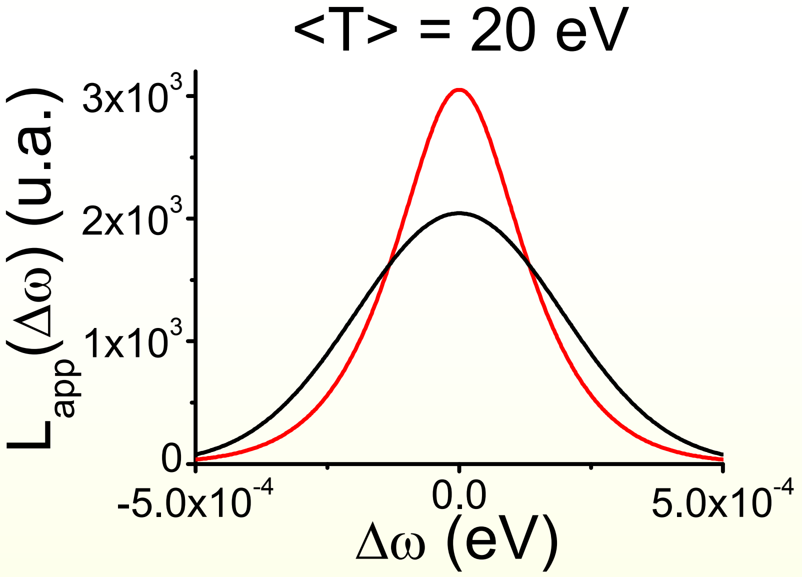
$$L_{app}(\Delta\omega) = \int W(T)\,B(T)\,L(\Delta\omega, T)\,dT$$

W : gamma law
B: maximum at 1.5 eV
L : Gaussian



<T> = 1 eV

Broadening



<T> = 20 eV

Narrowing

J. Rosato *et al.*, AIP Conf. Proc. **874**, 292 (2006)

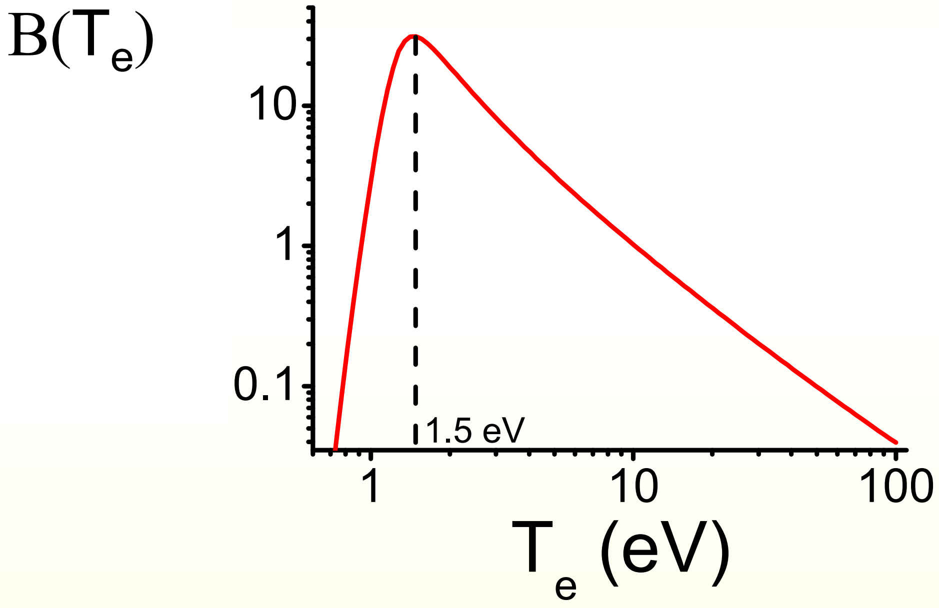
Summary

-Line shapes provide information on the plasma composition and parameters
-Access to the dynamics of the plasma (bulk motion, turbulent transport)

-Line shapes are powerful diagnostic tools in magnetic fusion but require detailed modelling for a full efficiency

-Passive spectroscopy well suited for ITER. Hostile environment asks for simple and sustainable diagnostics

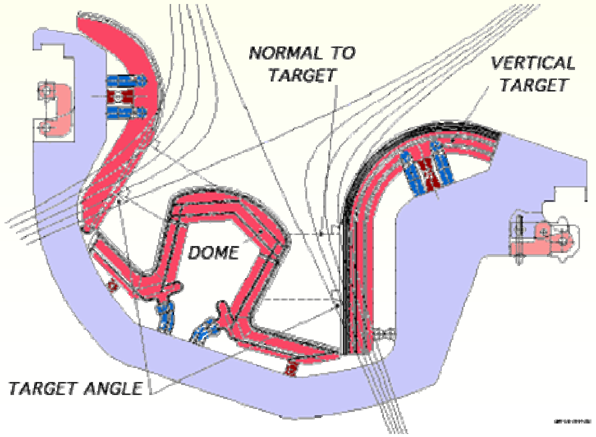
D_α Brightness B(T)



Line with high principal quantum number n

In a divertor the plasma is usually recombining

Hydrogen and helium lines up to n=20 may be observed



ITER divertor

For n > 8, Stark effect generally dominates the broadening

A standard Stark broadening approach is usually valid for n~10:

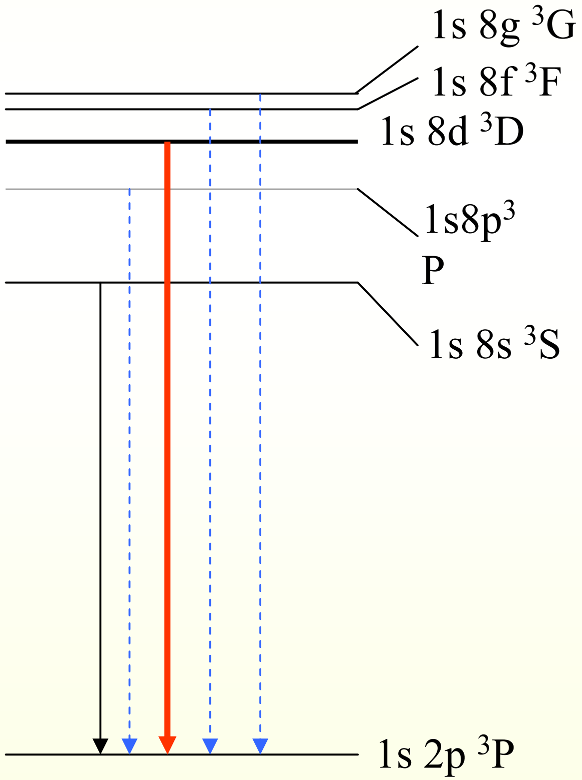
static ions, impact electrons

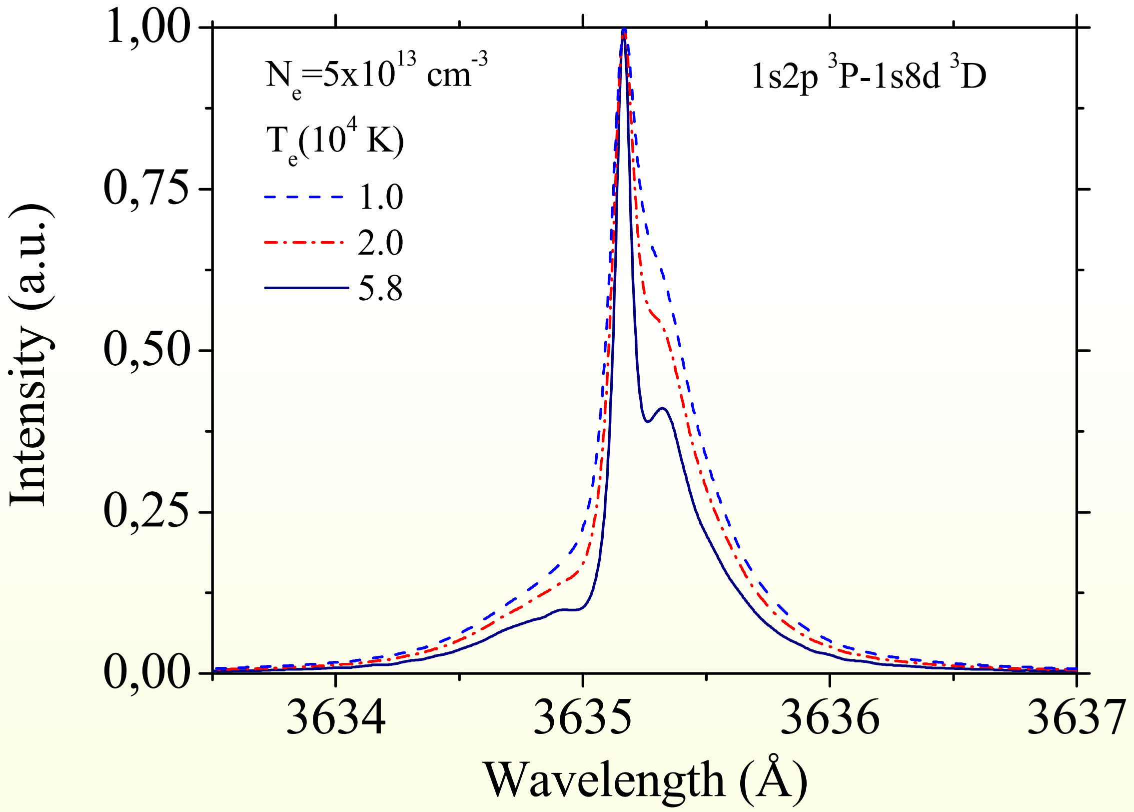
However for higher n values, non binary electron effect act on the emitter. A dynamic many body approach is requested.

The high n lines of helium are Stark broadened

8d ^3D – 2p^3P line of helium is Stark broadened

Forbidden components appear



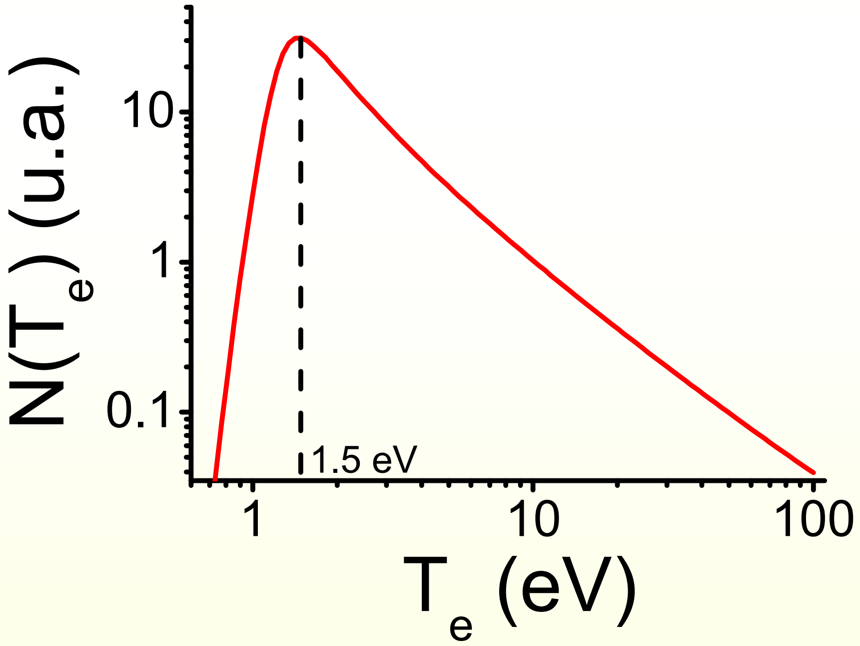


Effet Doppler - raie Dα

Profil de raie $$L(\Delta\omega, T_i) \propto \frac{1}{\sqrt{T_i}} \exp\left(\frac{-\zeta\Delta\omega^2}{T_i}\right)$$

population d'échange de charge

Population



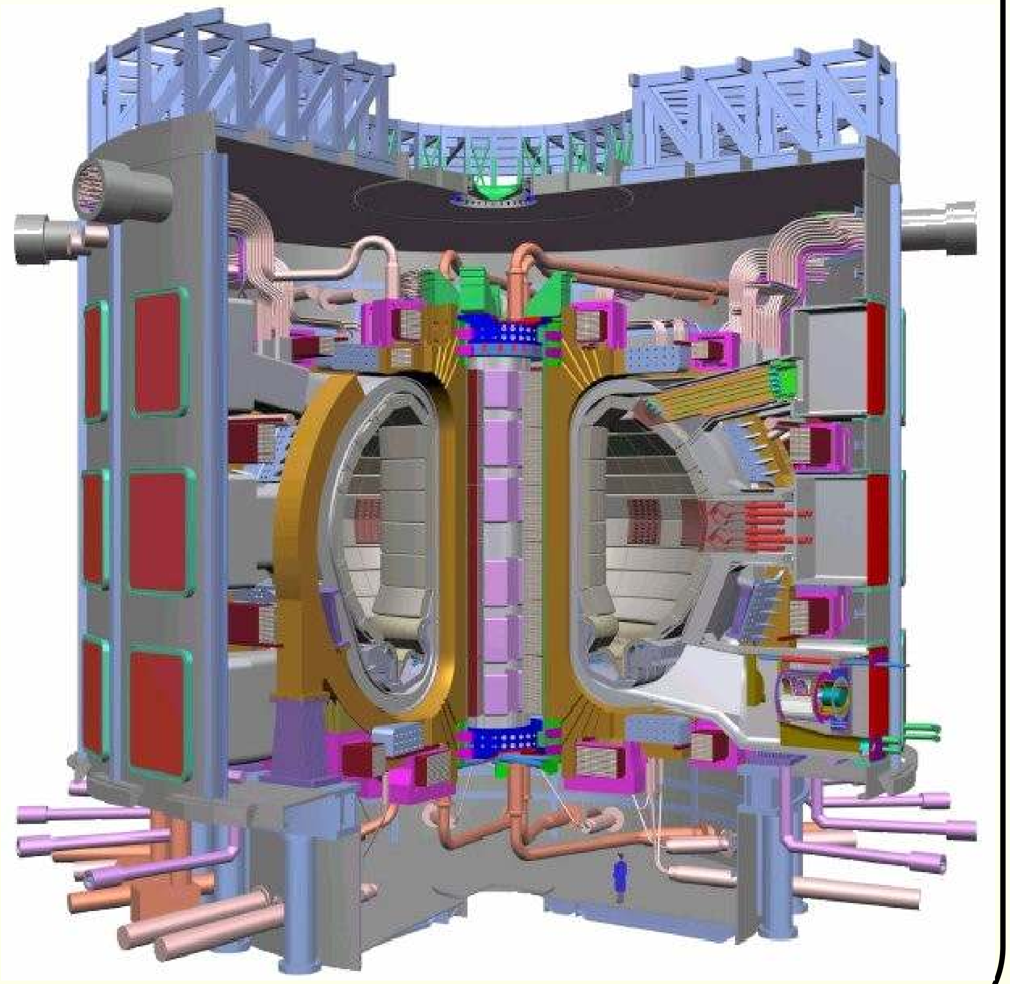
Etude du cas $T_e \approx T_i$

SPECTROSCOPY ON ITER

Like in present day tokamaks, spectroscopy will remain an essential source of information for ITER

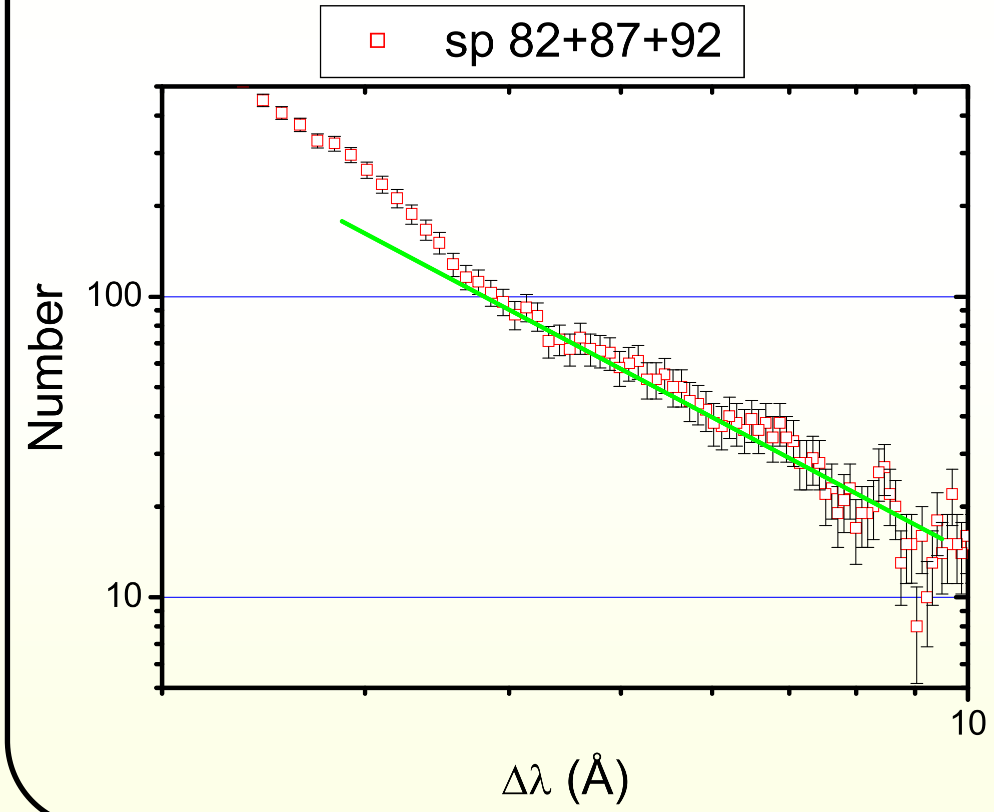
More than 10 spectroscopic diagnostics implemented :

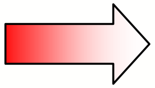
-Measures of N_e, T_e, T_i
-Impurity control
-Divertor optimization



D_α MEASUREMENTS AT THE EDGE OF TORE SUPRA

- Apparatus function Gaussian
- error bars study (statistical error)
- average on time to increase the statistics





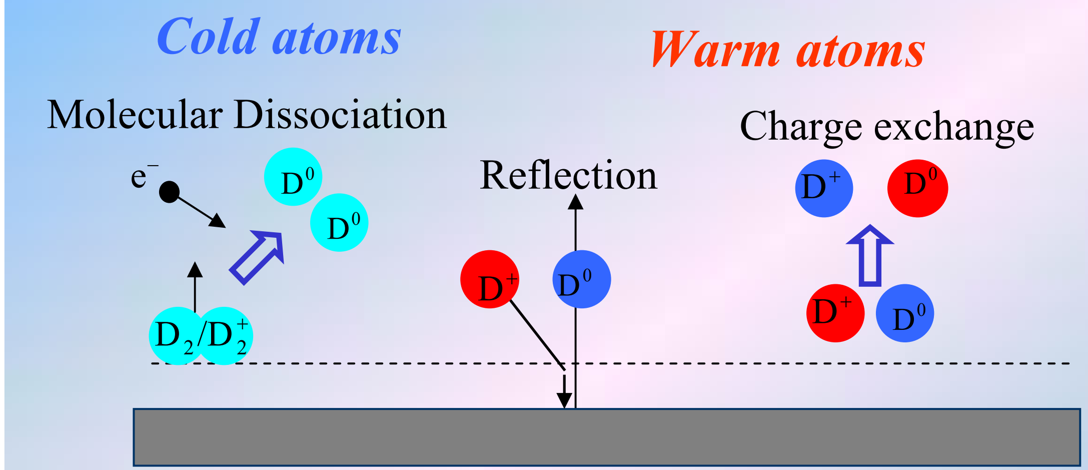
True signal

Thanks to the intensity of the line and the large integration time (100 ms)

Line shapes emitted by hydrogen isotopes

Several populations of neutrals, with completely different temperatures, coexist in the edge.

They originate from entirely different processes :



A specific signature of these populations is generally visible on the line shapes emitted by low n lines (Balmer α) of hydrogen isotopes

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Textor : J. Hey et al, J. Phys. B **37**, 2543(2004)

Tore Supra :Y. Marandet et al, Nuclear Fusion **44**, 118(2004)

Detailed line shapes for opacity calculations

In a magnetic field, Ly$_\alpha$ exhibits 10 components

Model for divertor plasmas:

-Ions and electrons treated with an impact model (H. Griem)

-Zeeman effect and fine structure retained

An analytic calculation has been developed (J. Rosato et al , 2006)

Such profiles are calculated repeatedly in the neutral transport code