Computer simulation of the effect of periodic electric fields on line shapes

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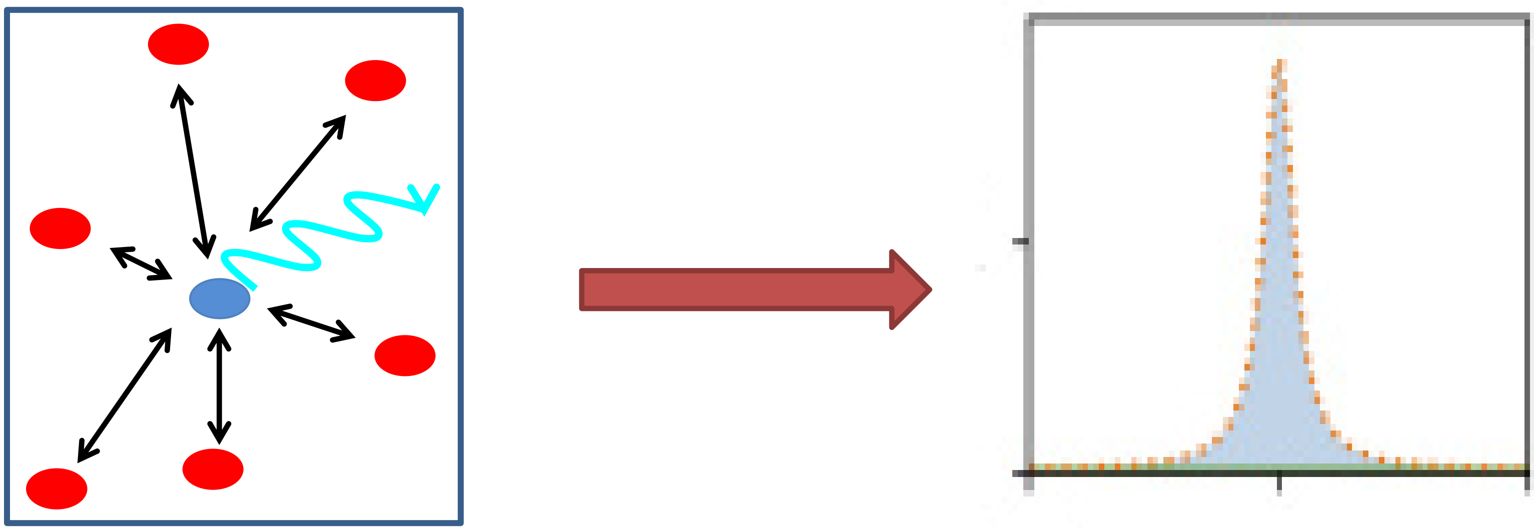
Outline

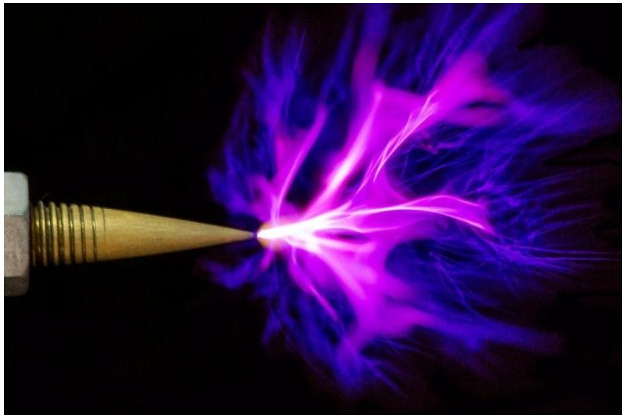
1. Introduction
2. Line shape model
3. Plasma and Langmuir wave simulations
4. Results
5. Summary

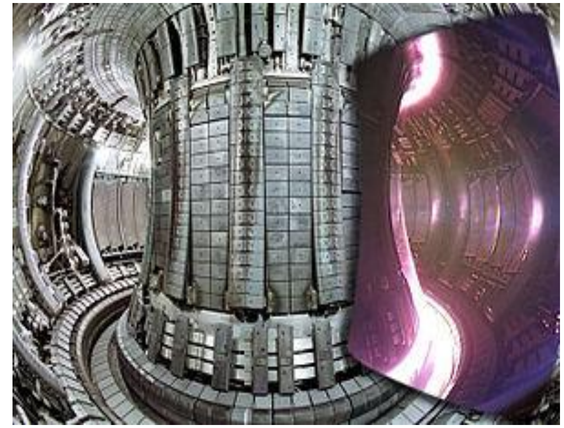
Plasma spectroscopy

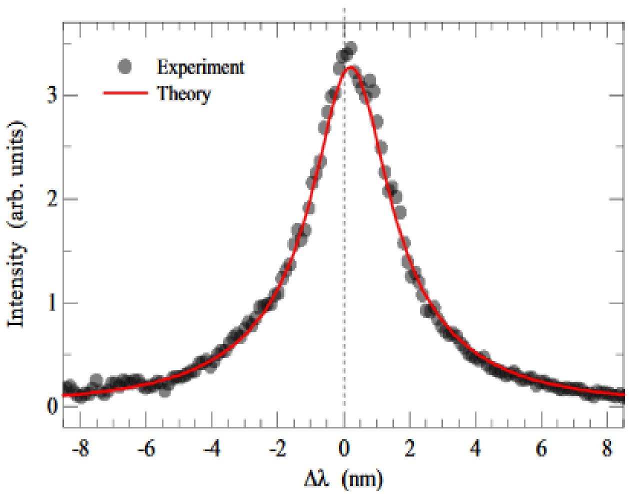


Spectroscopy is an efficient diagnostic tool for plasmas : an analysis of spectral line shape provides information on plasma parameters: temperature, density and presence of plasma turbulence.

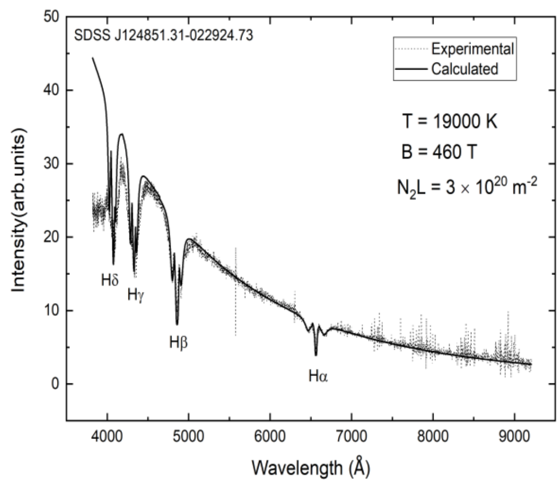
Line shapes for a plasma diagnostic



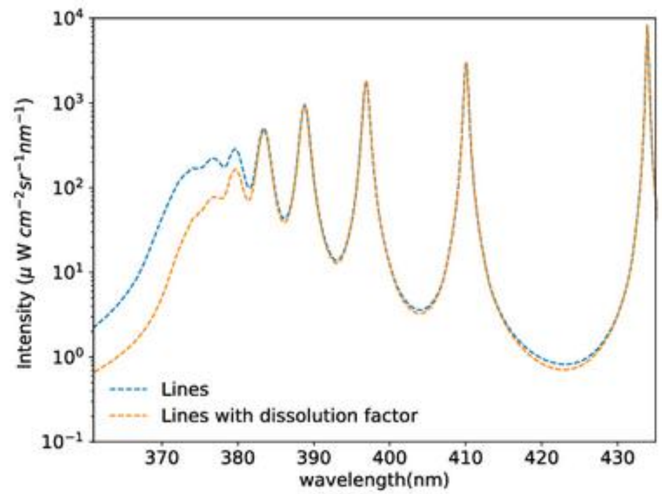




Sobczuk et al, Phys. Rev. E, 106, L023202, 2022



Raji et al, EPJ D, 75, 63, 2021



Koubiti et al, atoms, 7, 23, 2019

Waves in plasmas

Universal phenomena in plasmas, from lab micro discharge to space plasmas.

Can be excited in different ways: density or temperature gradients, collective motion of particles, presence of a beam.

In a nonthermal plasma (Plasma out of thermodynamic equilibrium) waves can be strongly amplified by instabilities (e.g. Langmuir waves)

An example is beam-plasma instabilities. Using kinetic theory (inverse Landau damping), it is possible to evaluate the magnitude of the amplified waves after saturation by non linear processes. Magnitude of Langmuir waves electric field E_w can be larger than the mean plasma microfield E_m

Effect of a simple oscillating field: absorption or emission of oscillating field quanta

Simple electric field oscillation

$$\vec{E}(t) = \vec{E}_W \cos(\Omega t + \varphi)$$

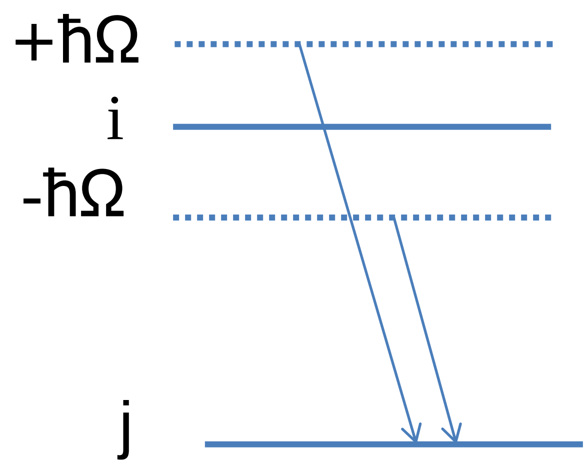
Quantum picture: the atom emits or absorbs a quantum of energy to the oscillating field

The atom is transiently in a virtual state separated in energy by $\pm\hbar\Omega$ from the initial state

The atom makes a transition to the final state j by emitting a photon with frequency $\omega_{ij} \pm \Omega$

Satellites appear on the line shape

(Blokhintsev, D., Phys. Z. Sow. Union 4, 501,1933)

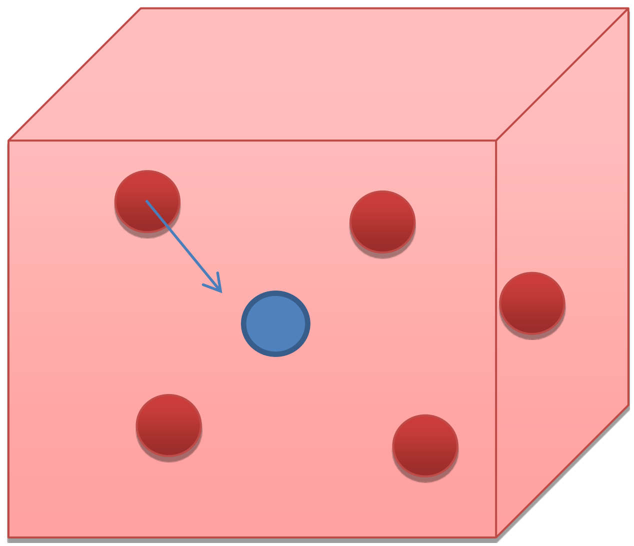


Effect of the stochastic plasma microfield

<u>Numerical simulation</u>

We use simulations of the electric fields created by a large number of particles.

•Particles in a cubic box
  moving on straight lines
•Periodic boundary conditions
•Screened ion field



Simple model for Langmuir wave

For each history we generate the initial positions of particles at random and sample their velocities with a Maxwellian law. The field acting on the emitter is the sum of the electron and ion fields and the oscillating field

$$\vec{E}(t) = \sum_i \vec{E_i} + \sum_e \vec{E_e} + \vec{E_L} \quad \text{and} \quad \vec{E}_L = \vec{E}_W \cos(\omega_p t + \varphi)$$

$\vec{E}_W$ can be in fixed or random direction and can has a fixed or sampled magnitude.

we propose to sample the oscillating field magnitude for each history, with a half-normal PDF:

$$P(F) = \frac{2}{\pi \langle E_W \rangle} \exp\left(-\frac{F^2}{\langle E_W \rangle^2} \right)$$

We compare $\langle E_W \rangle$ to the mean plasma microfield E_m

We will average over a large number of histories, each history corresponds to a different magnitude and direction

A complex quantum dynamics of the emitter

The presence of an oscillating field plus a stochastic microfield favours non adiabatic transitions (change of quantum state) and transient resonance effects during the time of interest

<u>All this is accurately retained by a numerical solution of the Schrödinger equation</u>

Simulation calculation of the line shape

Schrödinger equation for the emitter submitted to electric field

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

U(t) atomic evolution operator, D the dipole operator

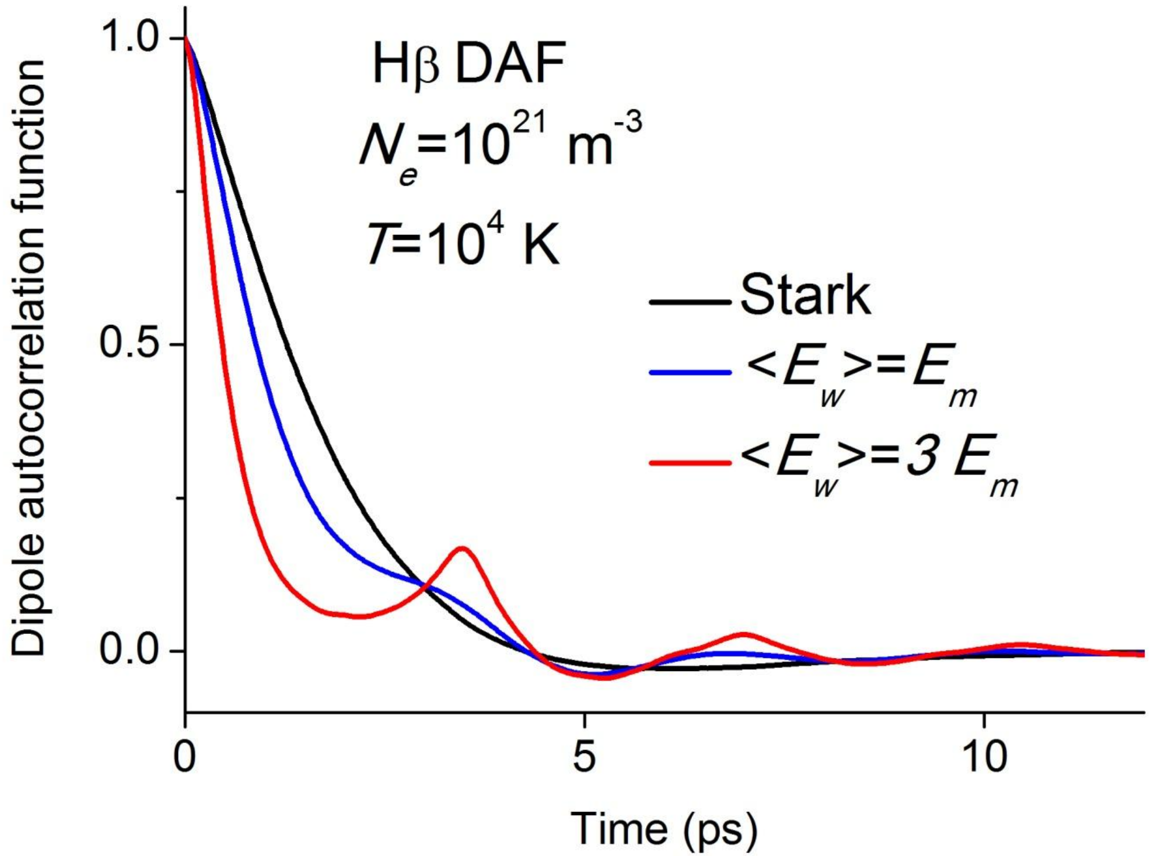
Integration of this equation for each field history
Calculation of the dipole autocorrelation function (DAF) obtained by arithmetic mean over a large number of field histories (3000)

$$C(t) = Tr\left\langle \vec{D}(0).\vec{D}(t)\,\rho \right\rangle$$

The line shape is obtained by the Fourier transform of C(t)

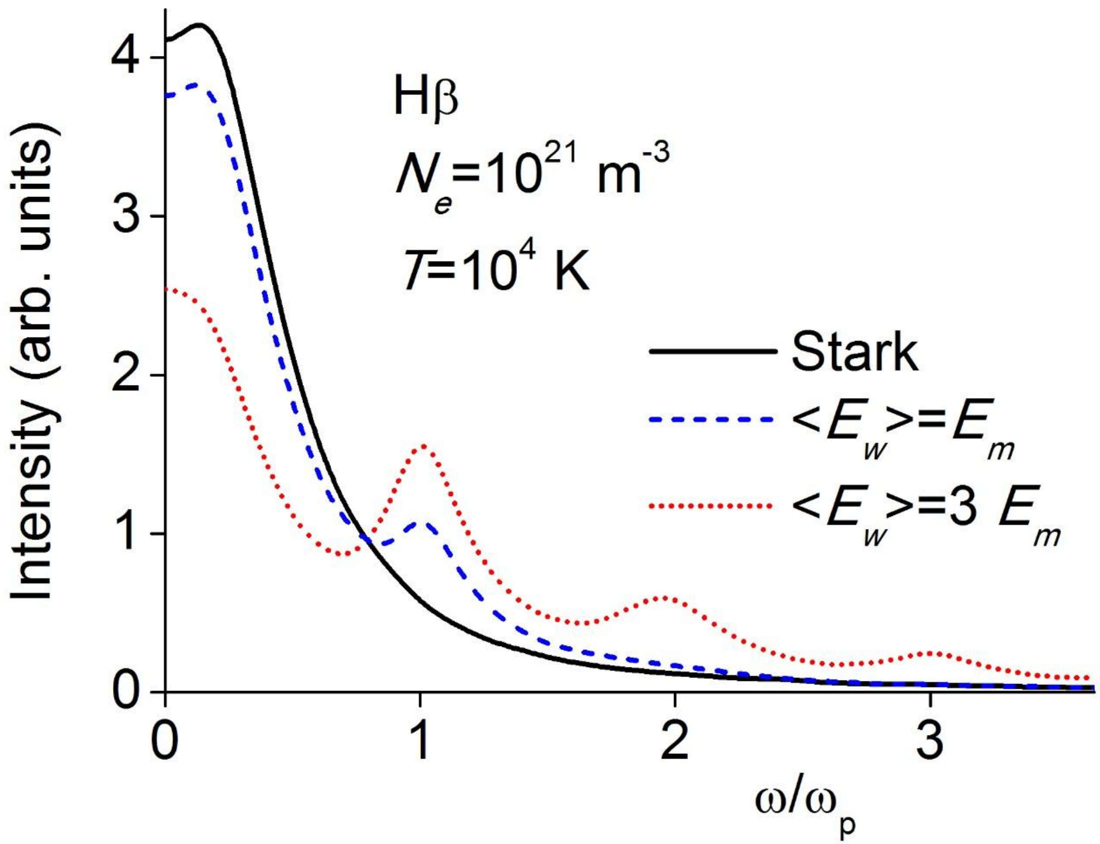
Results

Balmer β DAF, $N_e=10^{21}$ m^{-3}, T=10^4 K



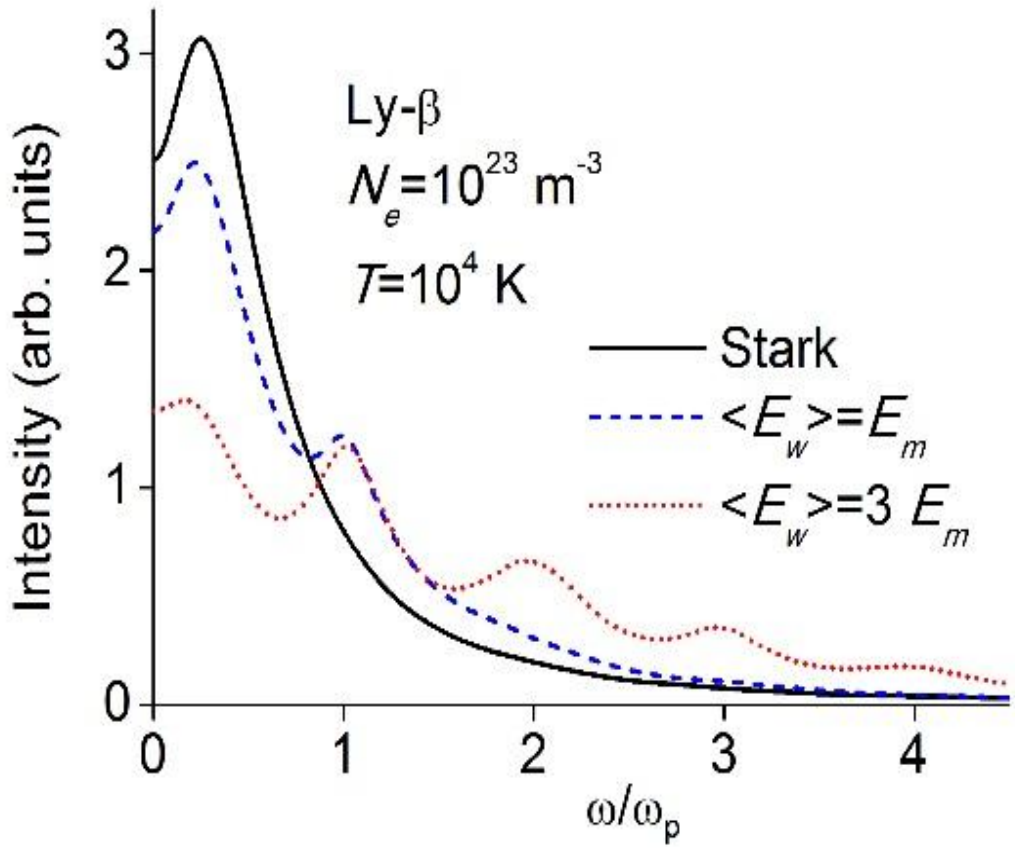
Dipole Autocorrelation Function

Balmer β (Hβ), N_e=10^{21} m^{-3}, T=10000 K



Pure Stark effect and 2 values of the wave magnitude

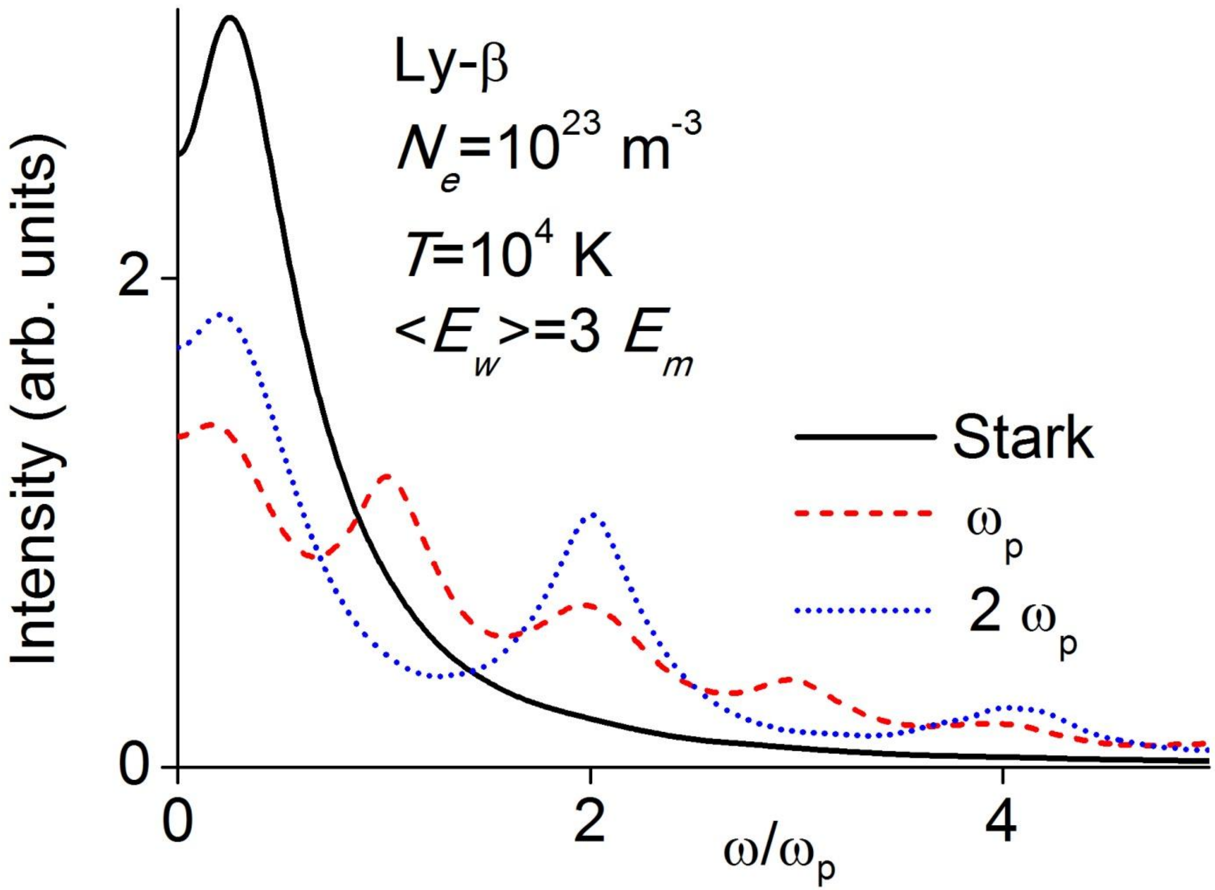
Lyman β (Ly-β)), $N_e=10^{23}$ m^{-3}, T=10000 K



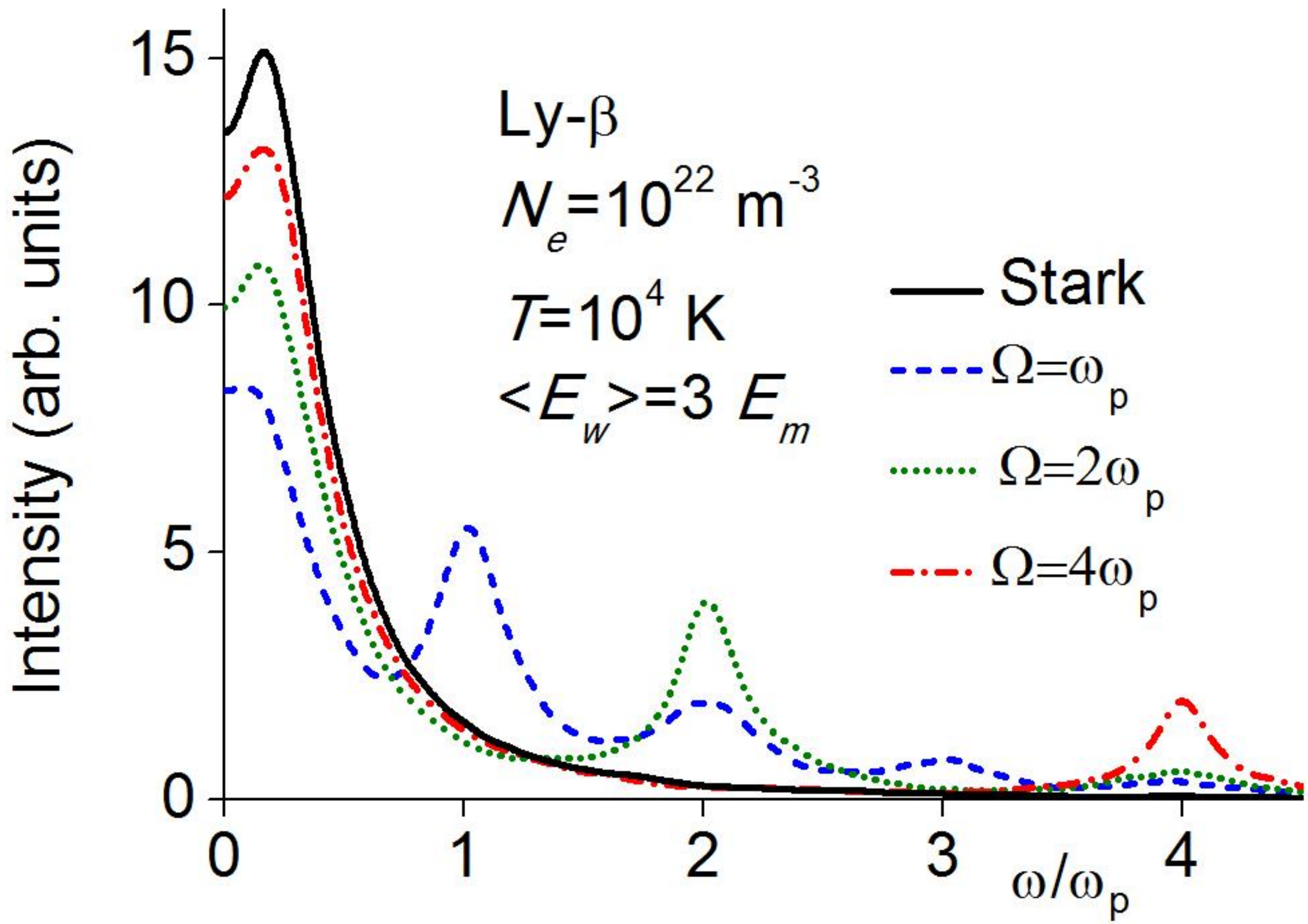
The transfer of intensity is increased with the magnitude of the oscillating electric field.

Effect of an oscillation frequency change

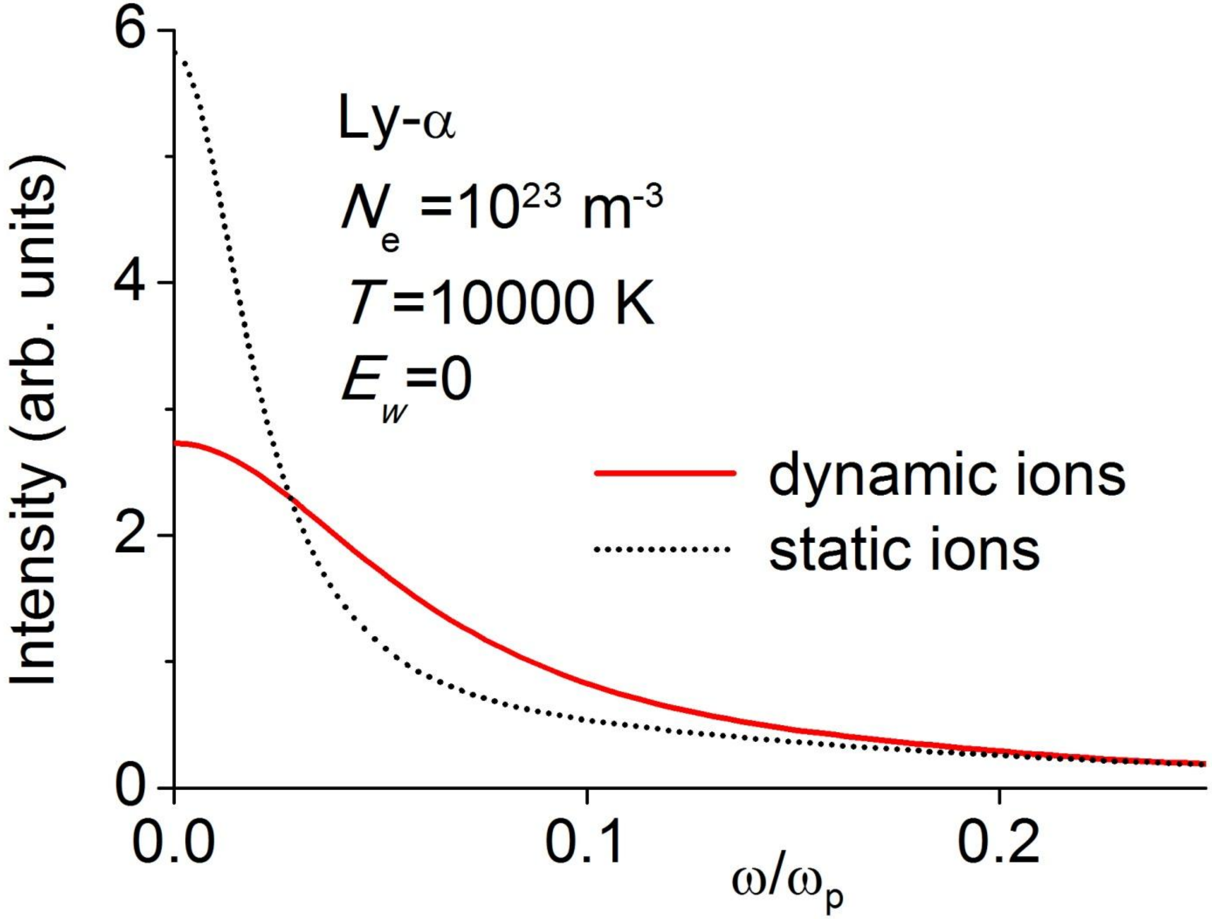
Ly-β, $\langle E_W \rangle = 3\ E_m$, $N_e = 10^{23}\ m^{-3}$, T=10000 K



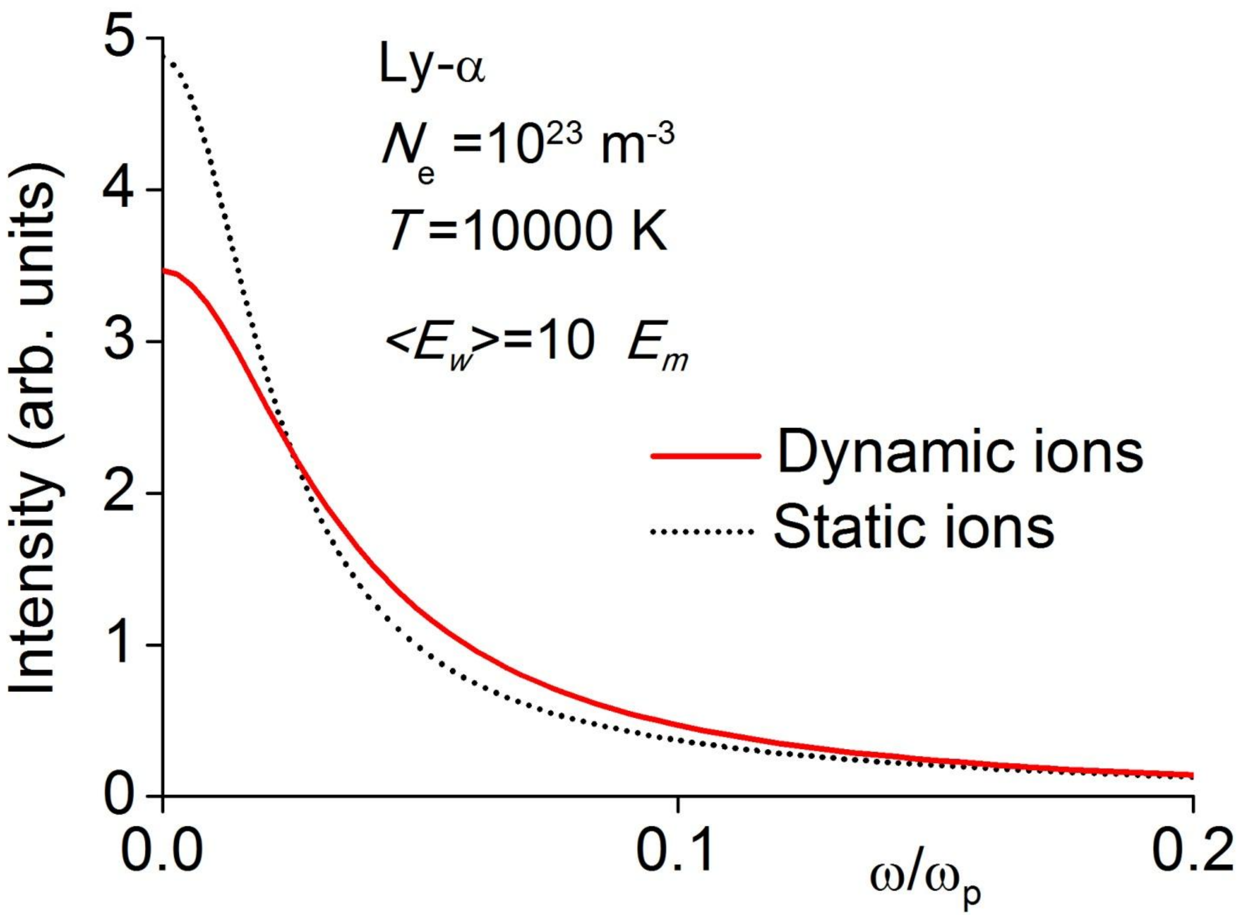
Ly-β, <E$_W$>=3 E$_m$, N$_e$=10^{22} m^{-3}, T=10000 K



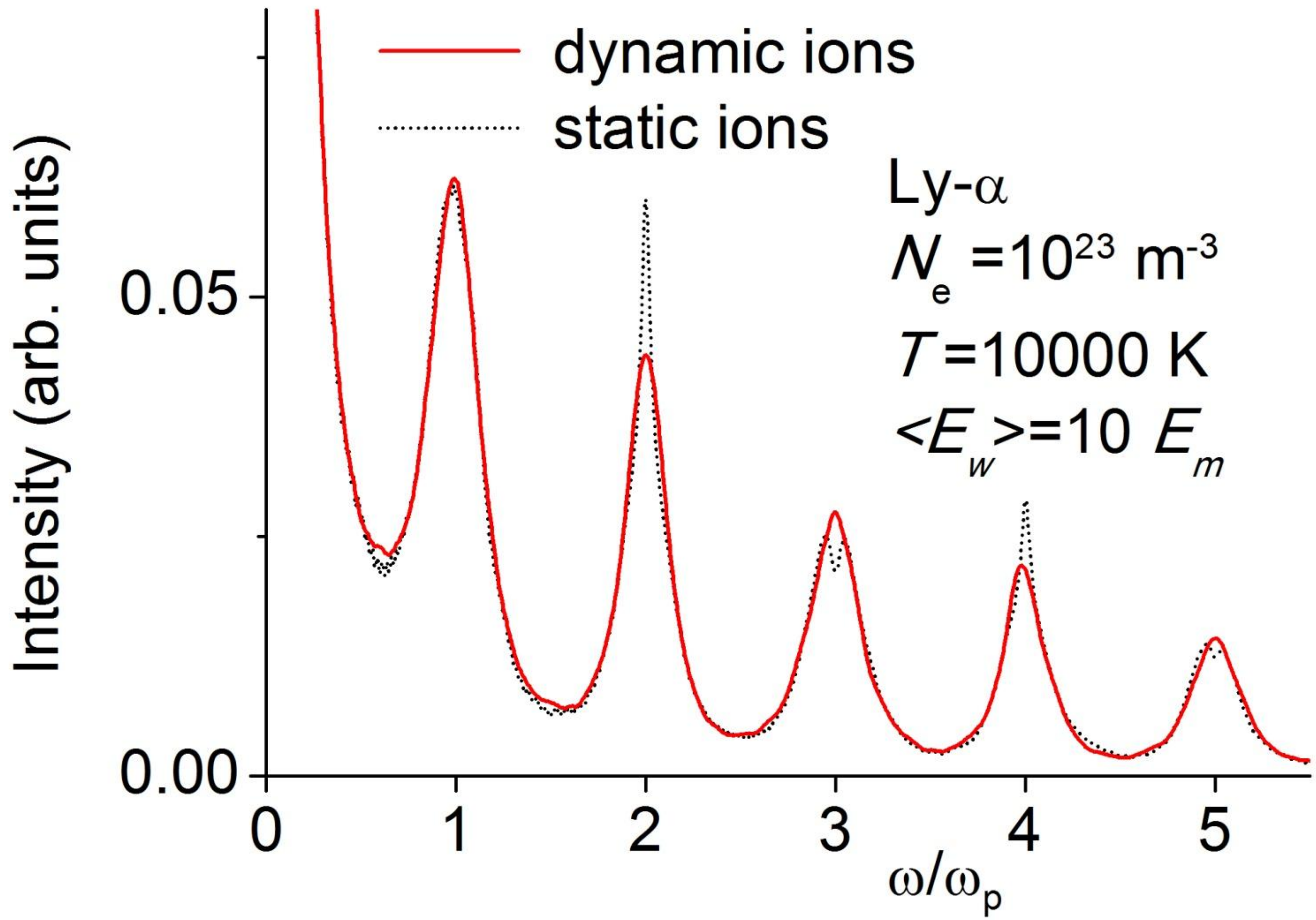
Ly-α without wave, $N_e=10^{23}$ m^{-3}, T=10000 K



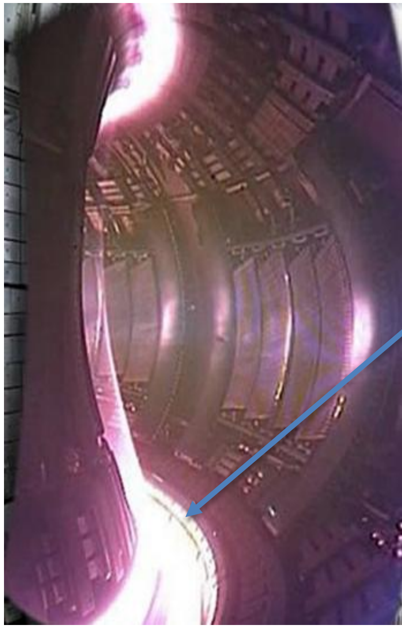
Ly-α with wave, $\langle E_W \rangle = 10\ E_m$, $N_e = 10^{23}\ m^{-3}$, T=10000 K



Ly-α, <E_W>=10 E_m, $N_e=10^{23}$ m^{-3}, T=10000 K

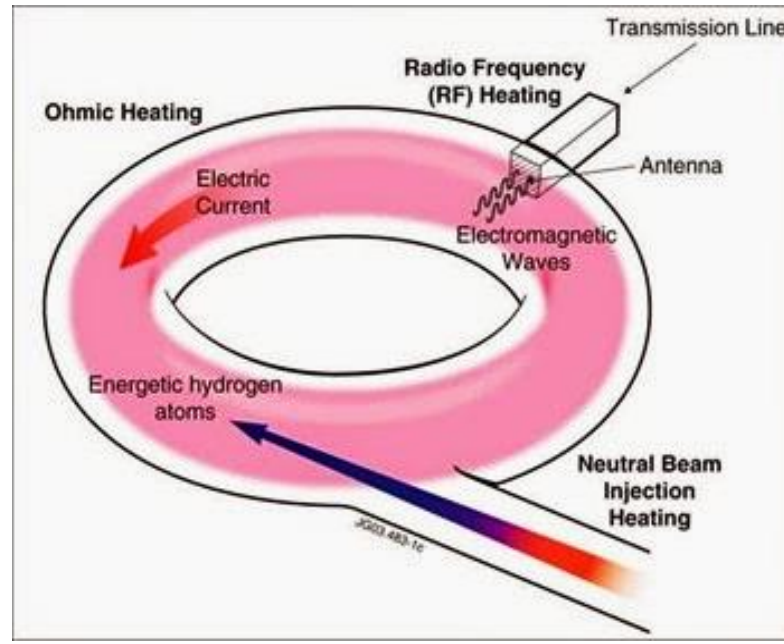


Edge plasma



Edge & divertor:

- Temperatures down to 1 eV, and less
- A large amount of neutrals can be present
- Strong atomic line radiation

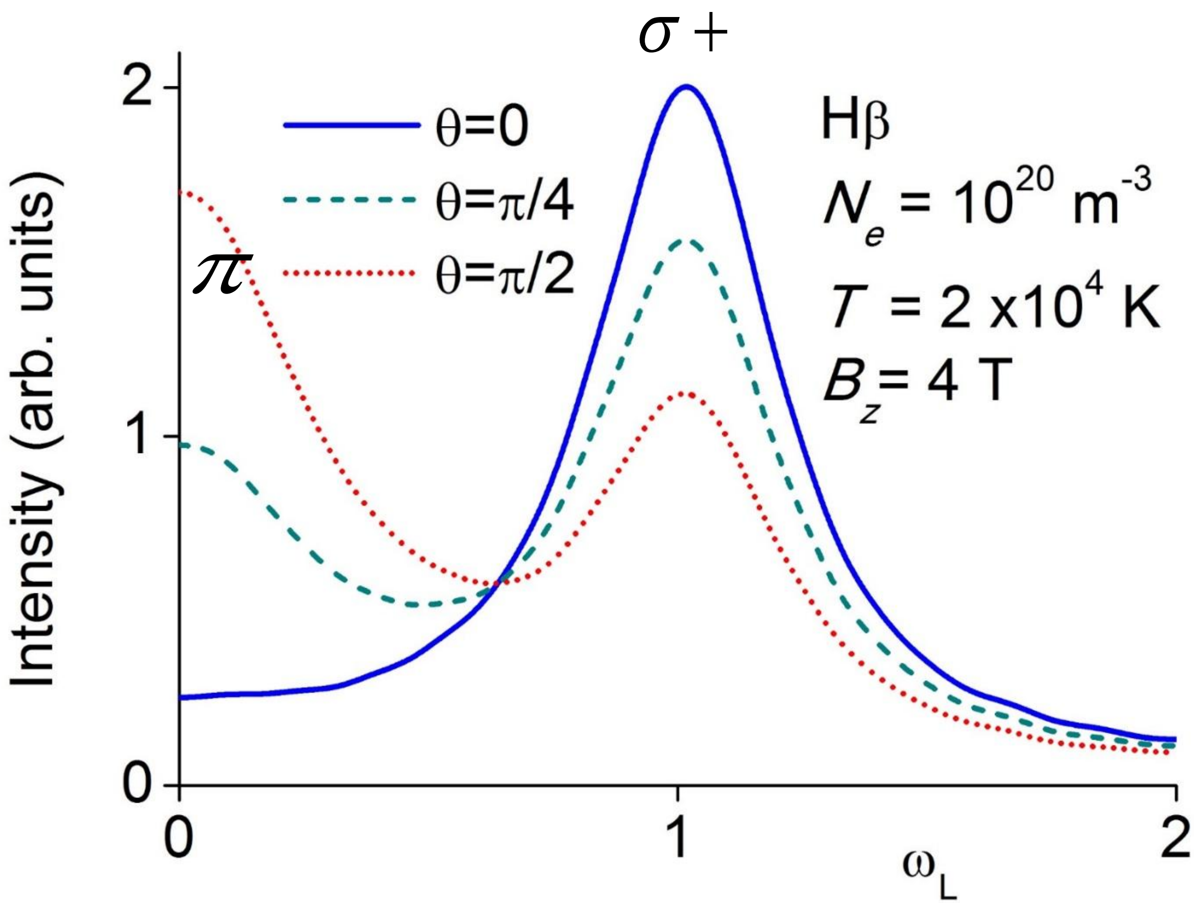


Radio frequency heating

Electron cyclotron resonance

Spectroscopy provides a efficent diagnostic tool

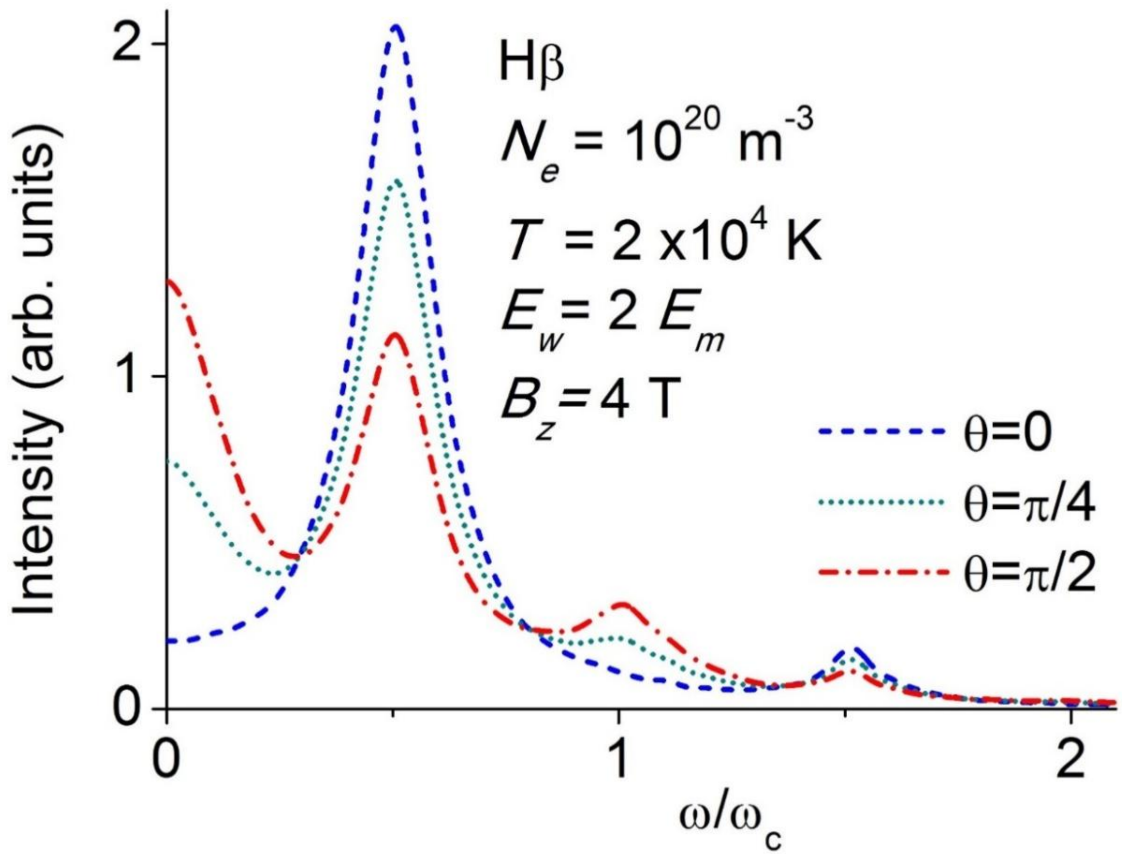
Hβ Zeeman-Stark line shapes for a magnetic field B_z=4 T and a line of sight angle θ with z



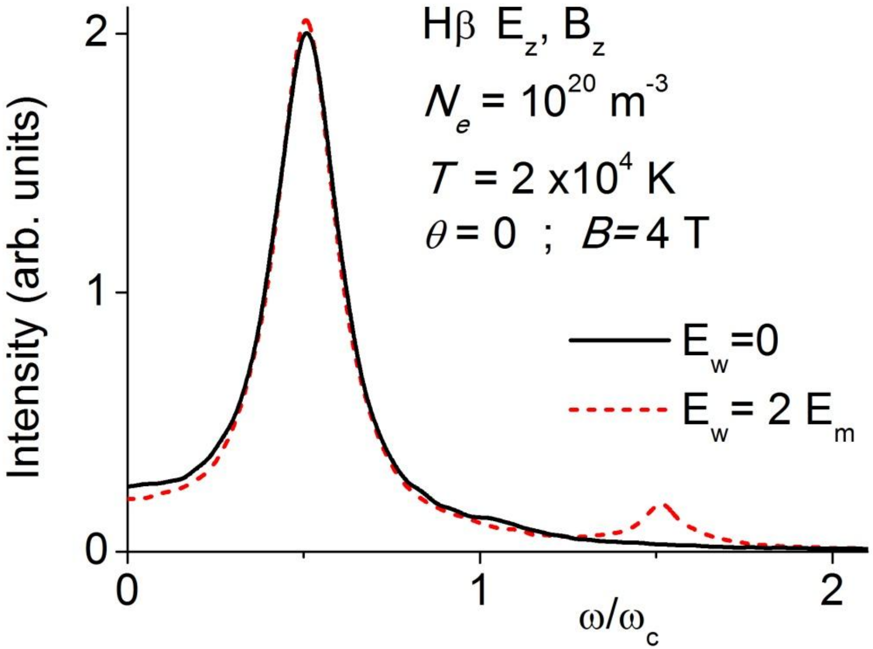
$$\omega_L = \frac{eB}{2m_e}$$

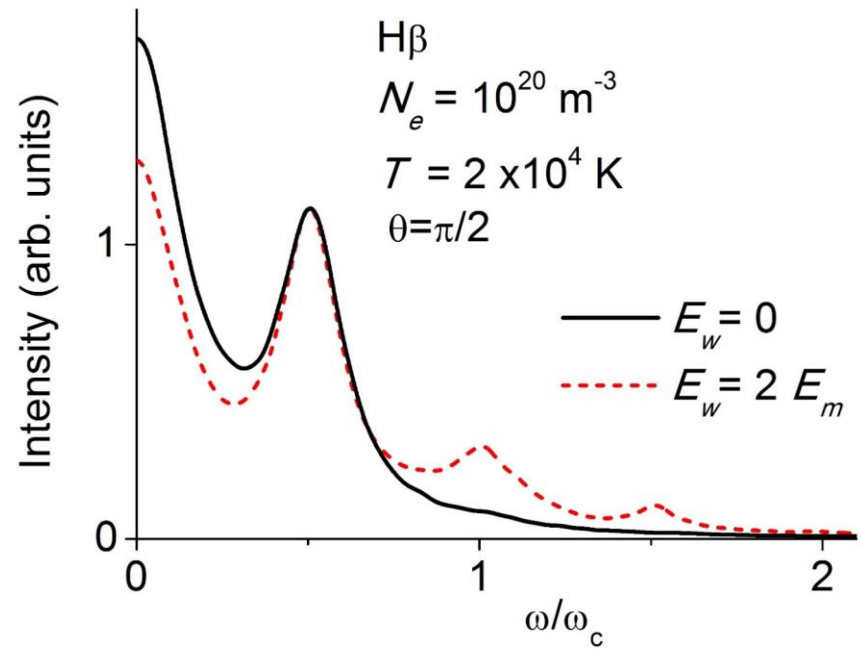
Effect of oscillation due a radiofrequency field at ω_c

Balmer β (Hβ), $N_e=10^{20}$ m^{-3}, T=2x10^4 K, E_{wz}= 2 E_m, B_z=4 T



Hβ profiles for a magnetic field B_z=4 T, with and without a wave E_w=2 E_m along z





$$\omega_c = 2\omega_L$$

Summary

Different simulation calculations all predict satellites

Satellite number is increased with an increase of oscillating field modulus

Width of the main line is changed by a transfer of the central intensity of the line to satellites structures, which give a possibility to diagnose both the plasma and the wave parameters.

Simultaneous simulation of ion dynamics and oscillating field are required for a realistic line profile.

Perspective

Report in preparation of the workshop on codes comparison SLSP (Spectral line shape in plasma, Hyères October 2022)

Good overall agreement for the effect of periodic field between the results of several codes :

- ERIP: University of Valladolid
- HSTRKII: University of Crete
- SimU:Weizmann Institute of Science
- Xenomorph: University of Texas

We plan to study :

Polarization effect
Zeeman-Stark effect
Application to different kind of plasmas
Arbitrary emitter (use of PPP code at PIIM lab)