Simulation Calculations of hydrogen lines submitted to oscillating electric field

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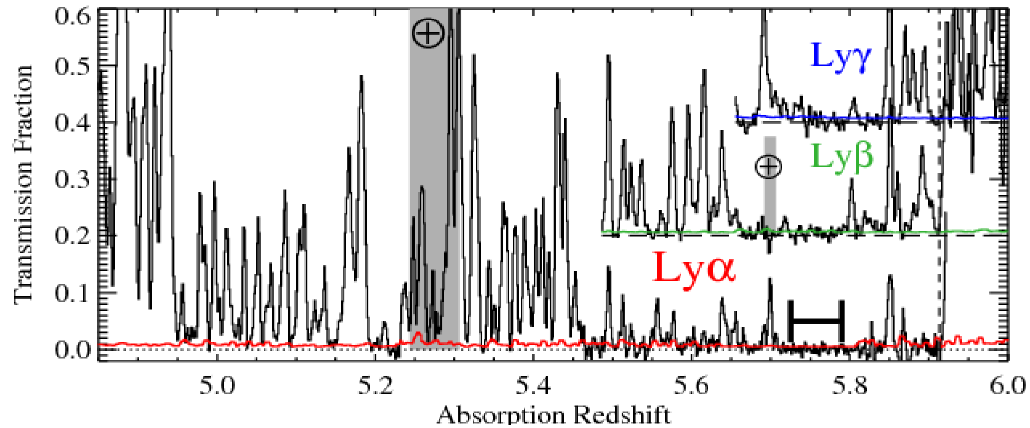
Outline

1. **Introduction**
2. Line shape model
3. Results: convolution simulations
4. Ab initio simulations
5. Summary

Line studies in plasmas submitted to waves

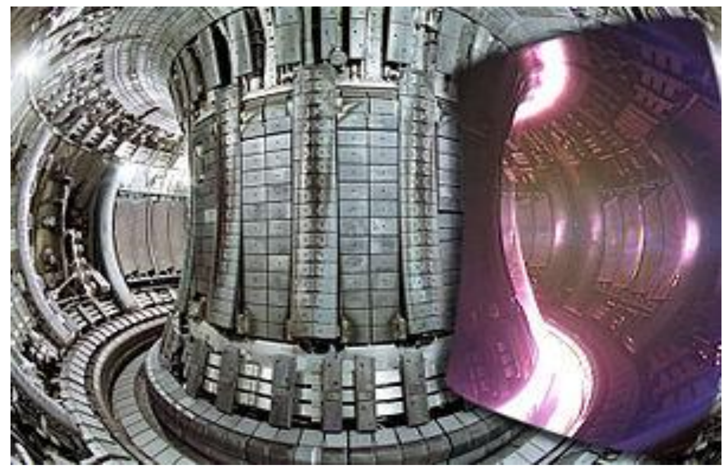
Line shapes for a plasma diagnostic

-Broadening : mainly Stark effect



Applied to
-Laboratory plasmas
-Fusion
-Astrophysics

Astrophysics



tokamak JET, ITER

Modeling of plasma radiative properties

<u>Numerical simulation</u>

We use simulations of electric fields, coupled to a numerical integration of the Schrödinger equation

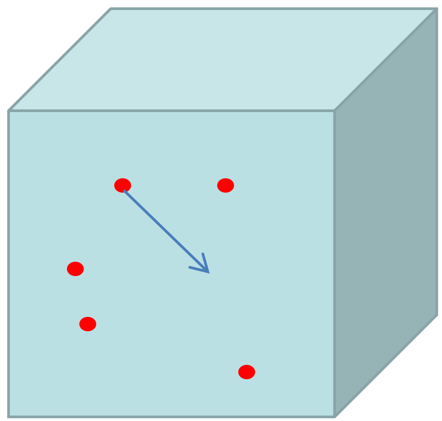
Not a molecular dynamics simulation:

particles move on straight lines

Cubic box

Periodic boundary conditions

Screened ion field



<u>Stochastic process</u>

Statistical properties of the plasma and waves

Plasmas and oscillating electric fields

Many different phenomena

-Fields created by an external source (microwave generator, laser radiation)

-Plasma oscillations : collective phenomena favor the development of fluctuations and oscillation. A wave may be amplified by an instability (e.g. beam-plasma instability) which increases the electric field modulus.

High amplitude oscillating fields are also present in astrophysical plasmas

In fusion plasmas : Tokamak plasmas strongly affected by waves

Spectra modified by oscillating fields can be used for a plasma diagnostic:

Klepper et al., Phy. Rev. Lett. **110**, 215005 (2013)

Effect of oscillating fields on line shapes

- Theory

  - Studies can be traced back to Blokhintsev (Blokhintsev D. I., Phys. Z. Sow. Union 4. 501 (1933))

  In presence of a field E cos(Ωt) , there is a possibility of observing satellites of the main line separated by $\pm\,\Omega$, $\pm\,2\Omega$, … $\pm\,j\Omega$

- - Mozer and Baranger, Oks and Sholin,..

  Waves can broaden, create satellites, holes on the lines, depending on plasma conditions

- Early experiments (W. R. Rutgers and H. de Kluiver, Z. Naturforsch, 29 a, 42 (1974)) : observation of satellites on Balmer lines at multiples of the electronic plasma frequency ω_p

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Simulation calculation of the line shape

Schrödinger equation for the emitter submitted to electric fields

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

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

$\vec{E}_S$ thermal Stark microfield, $\vec{E}_W$ wave field.

Integration of this equation for each field history

Calculation of the dipole autocorrelation function (DAF) obtained by an arithmetic mean over a large number (3000) of field histories

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

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

Plane waves

Field created by an external generator or Langmuir waves

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

Different kinds of simulations

- Convolution of a Stark profile with a profile affected by oscillating field
- Ab initio simulation of the dynamic ion field plus the oscillating field (but impact electrons)

- Fixed field simulation
- Sampled field simulations

  For each history E_m is sampled with a Probability Density Function (PDF), e.g. Gaussian (Langmuir waves)

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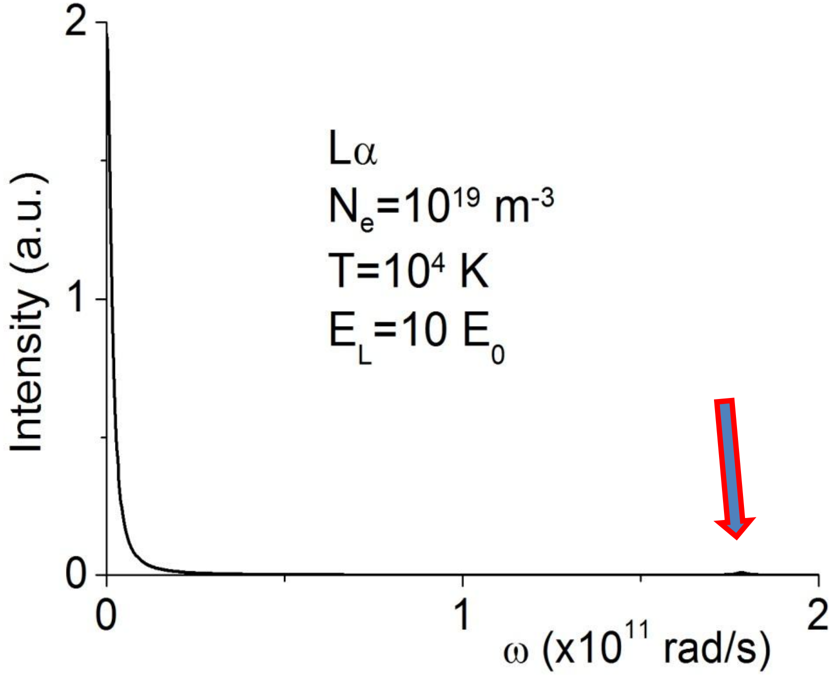
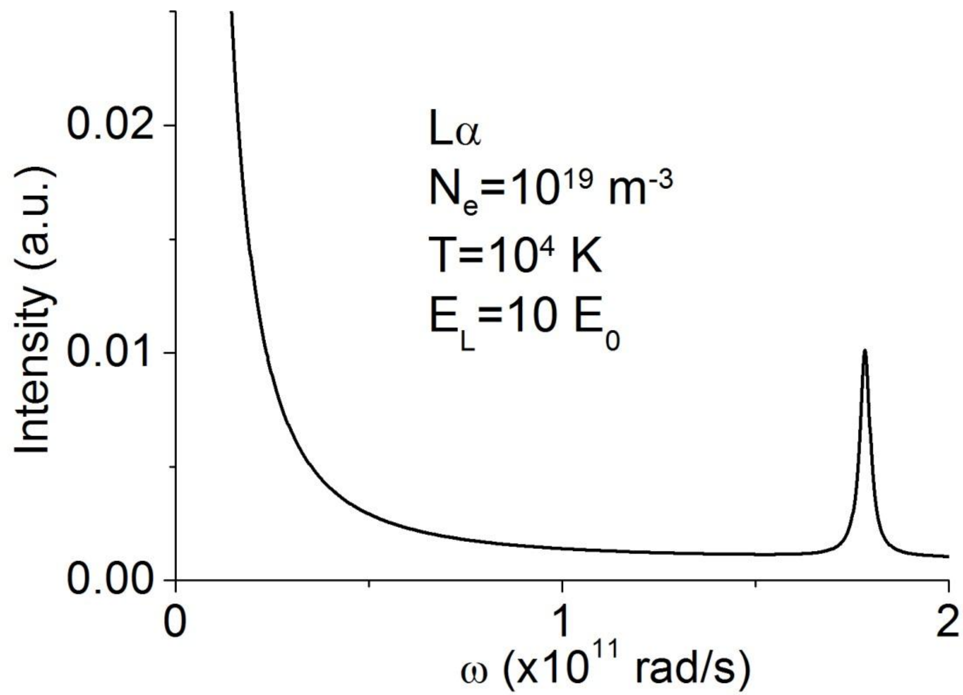
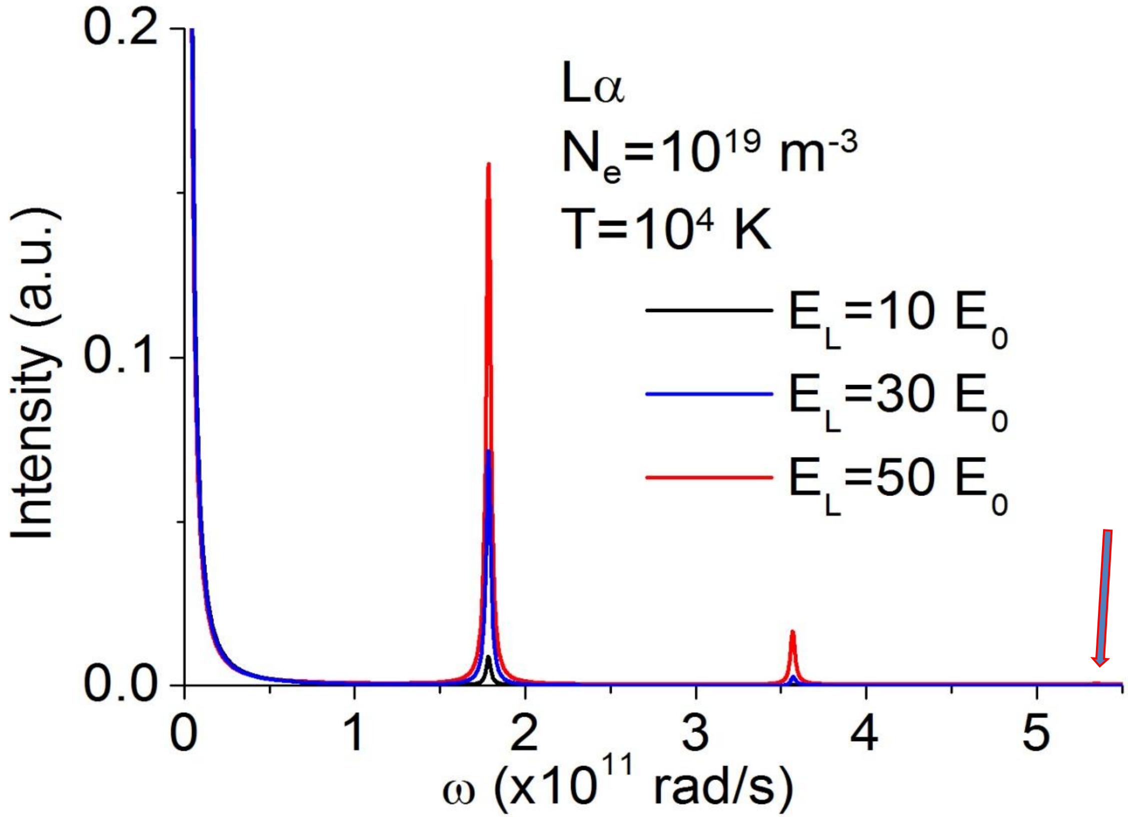
Lyman α, $N_e=10^{19}$ m^{-3}, fixed field





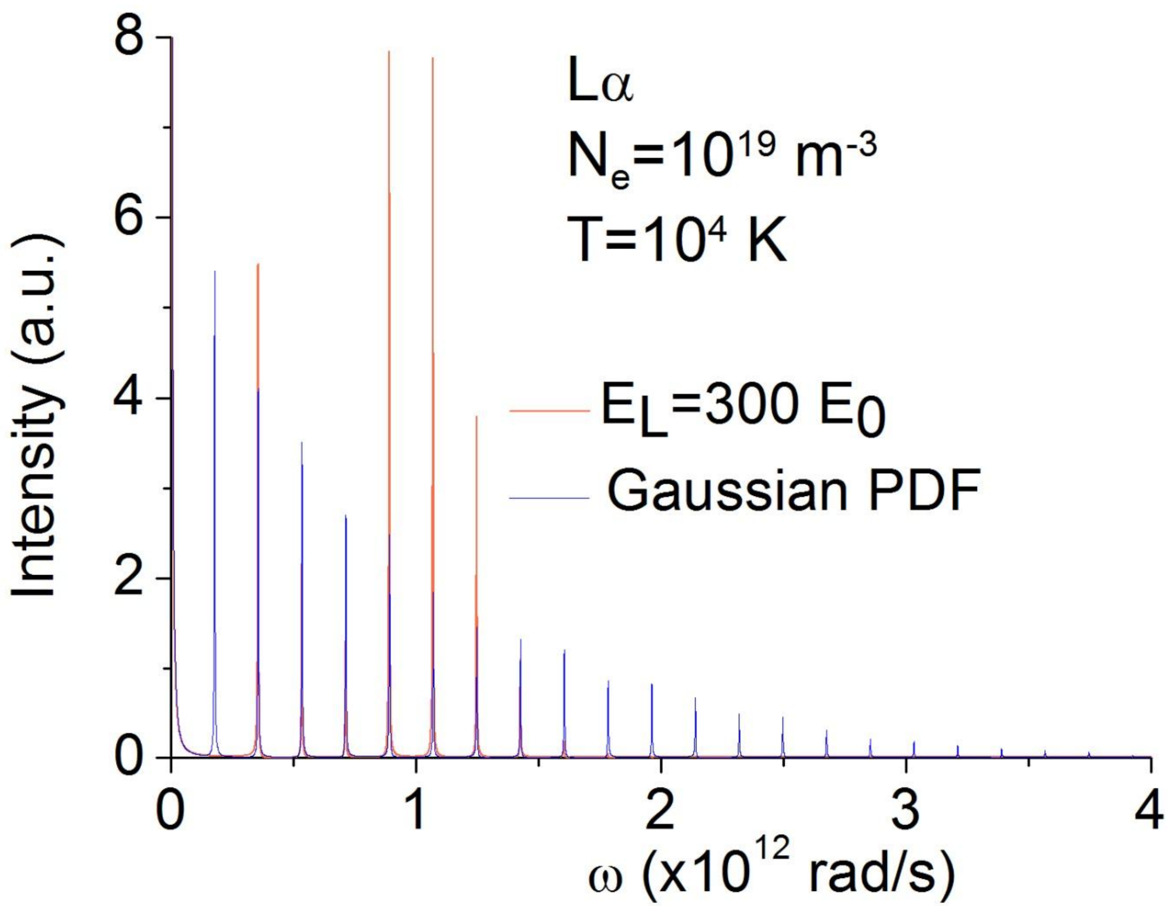
A satellite appears at ω_p, in the far wing,
with a weak intensity for $E_L=10\ E_0$

Lyman α, $N_e=10^{19}$ m^{-3}



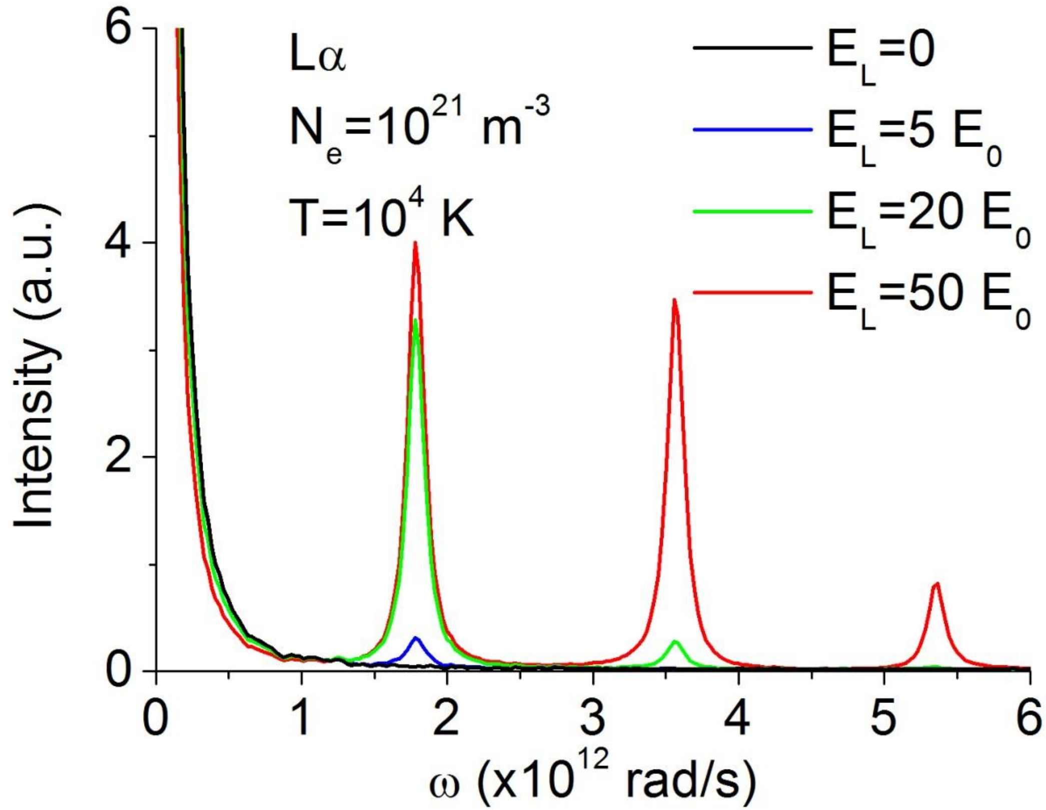
$E_L=10\ E_0$, 1 satellite at ω_p, (plus 1 at $-\ \omega_p$, not shown)
$E_L=30\ E_0$, 2 satellites at ω_p, $2\ \omega_p$
$E_L=50\ E_0$, 3 satellites at ω_p, $2\ \omega_p$, $3\ \omega_p$

Lyman α, $N_e=10^{19}$ m^{-3}, $E_L=300$ E_0 (5 MV/m)



$E_L=300$ E_0 , 9 satellites
Gaussian PDF, about 25 satellites

Lyman α, $N_e = 10^{21}$ m^{-3}

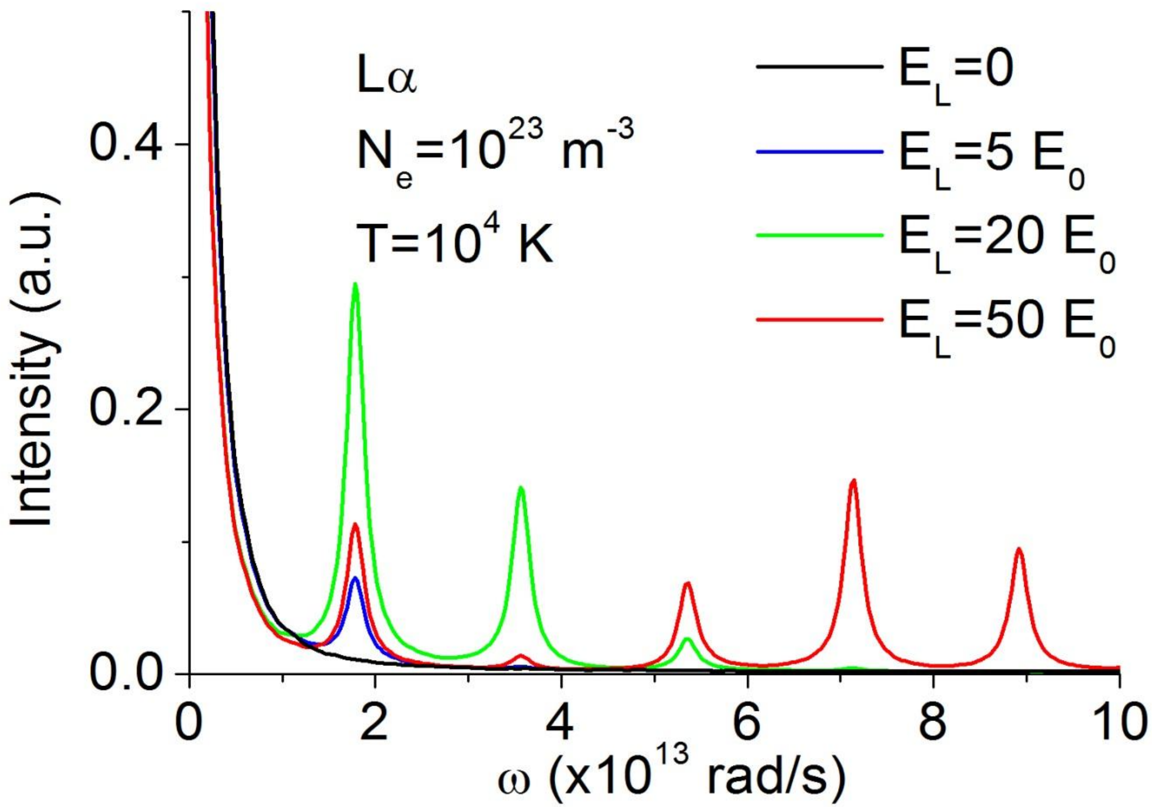


$E_L = 5\ E_0$, 1 satellite at ω_p,

$E_L = 20\ E_0$, 3 satellites at ω_p, 2 ω_p, 3 ω_p

$E_L = 50\ E_0$, 5 satellites at ω_p, 2 $\omega_{p,}$ 3 $\omega_{p,}$ 4 ω_p, 5 ω_p

Lyman α, $N_e=10^{23}$ m^{-3}

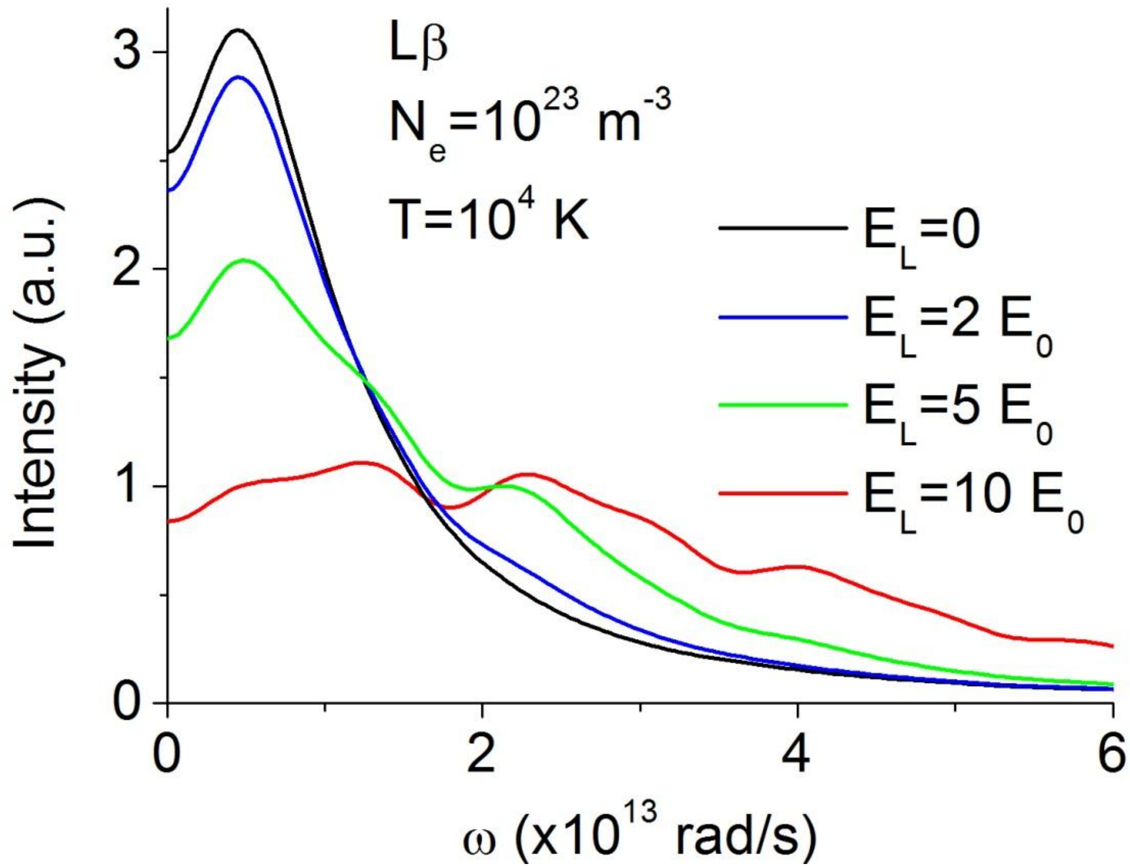


$E_L=5\ E_0$, 1 satellite at ω_p,

$E_L=20\ E_0$, 4 satellites at ω_p, 2 ω_p,.. 4 ω_p

$E_L=50\ E_0$, 8 satellites at ω_p, 2 $\omega_{p,}$ …, 8 ω_p

Lyman β, $N_e = 10^{23}$ m^{-3}



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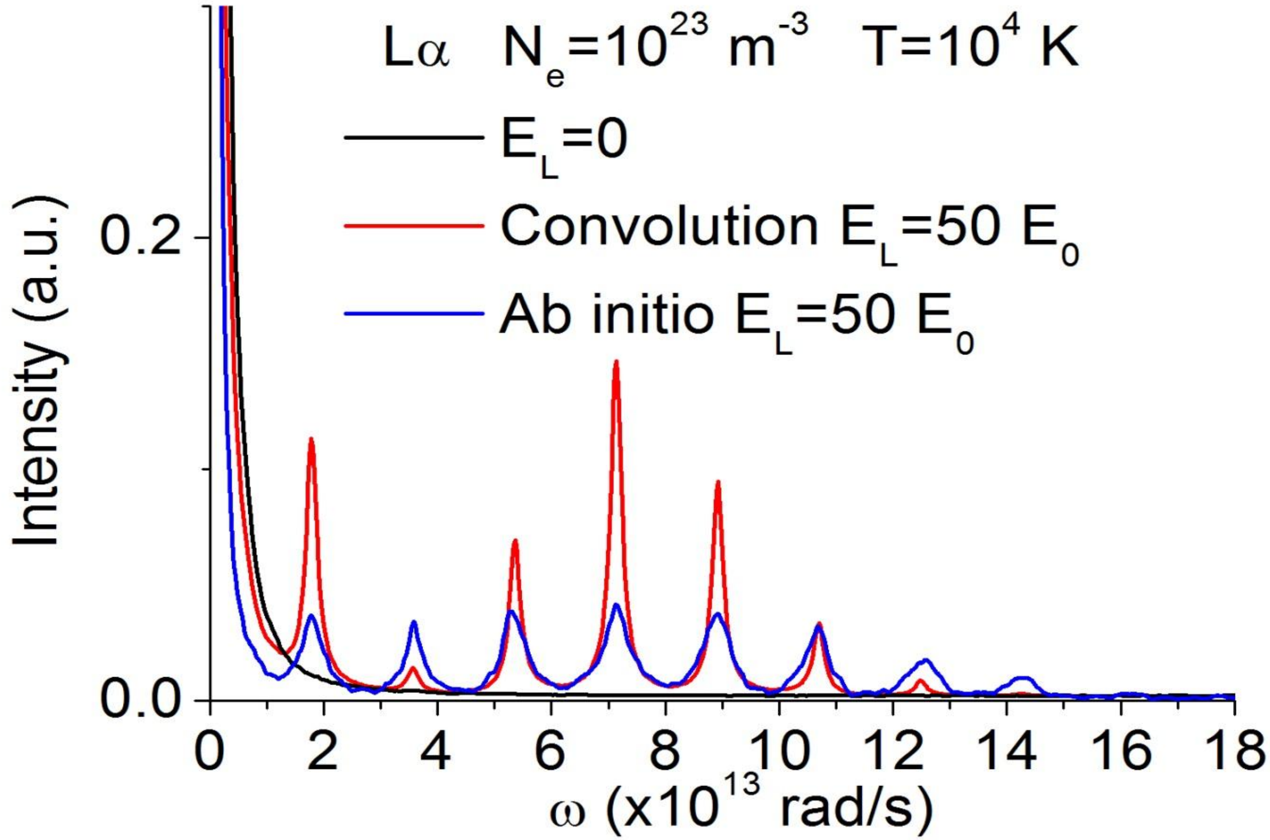
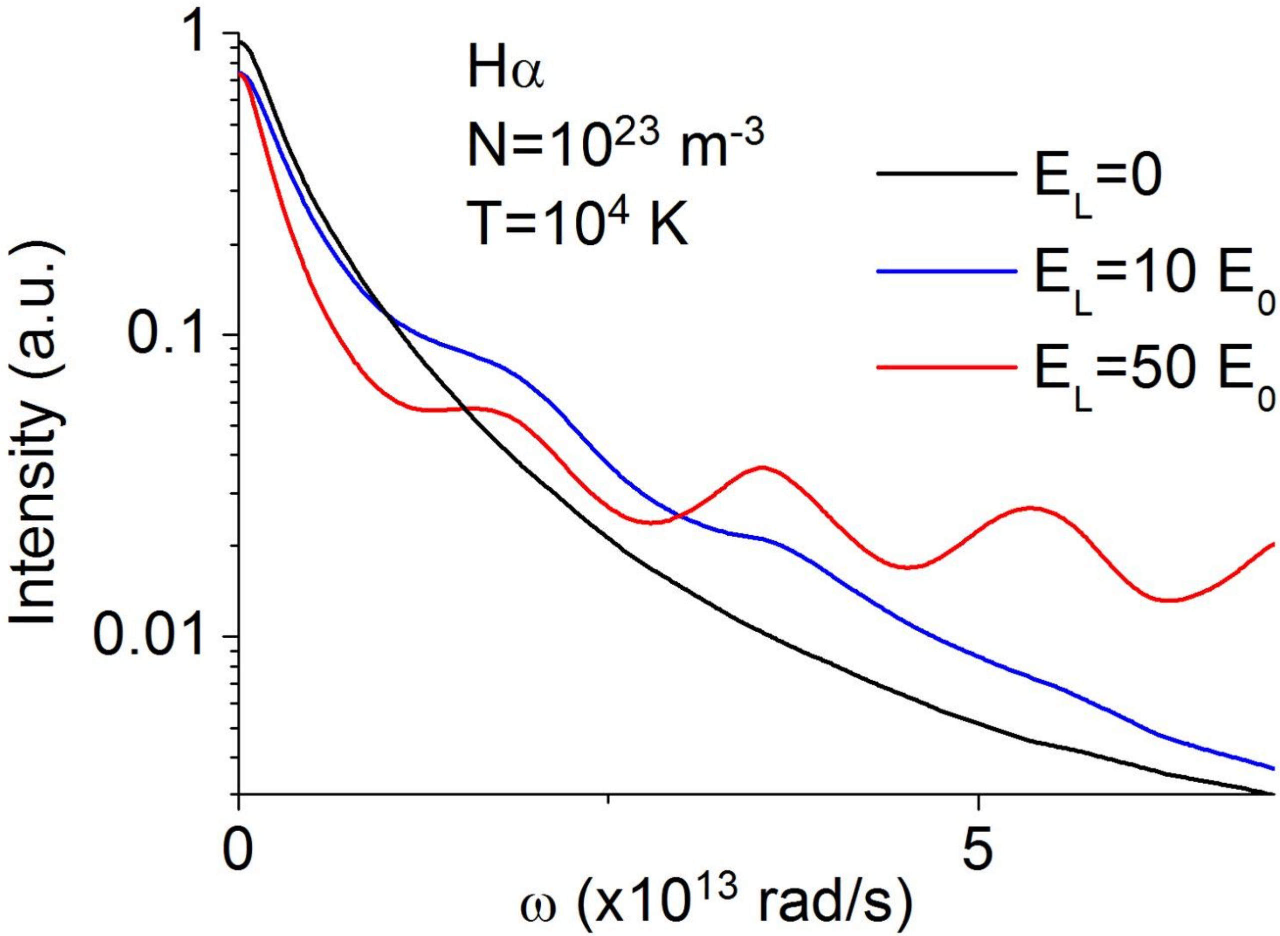
Lyman α, $N_e=10^{23}$ m^{-3}



An ab initio calculation broadens and transfers more intensity into the satellites as compared to a convolution : width of main line reduced by a factor 2.4

Balmer α, N_e=10^{23} m^{-3}, ab initio



Summary

Different simulation calculations all predict satellites

Satellite number is increased with an increase of oscillating field modulus

Satellites are sharp in convolution simulation, but get broader if an ab initio simulation is used

Width of the main line can be strongly modified

Simultaneous simulation of ion dynamics and oscillating filed are required for a realistic line profile : more on next talk