Effect of turbulence on line shapes in astrophysical and fusion plasmas

Ibtissem Hannachi [1,2], Mutia Meireni [1], Paul Génésio [1], Joël Rosato [1], Roland Stamm [1] and Yannick Marandet [1]

1 Aix-Marseille Université, CNRS, PIIM UMR 7345, 13397 Marseille Cedex 20, France
2 PRIMALAB, Faculty of Sciences, University of Batna 1, Batna, Algeria

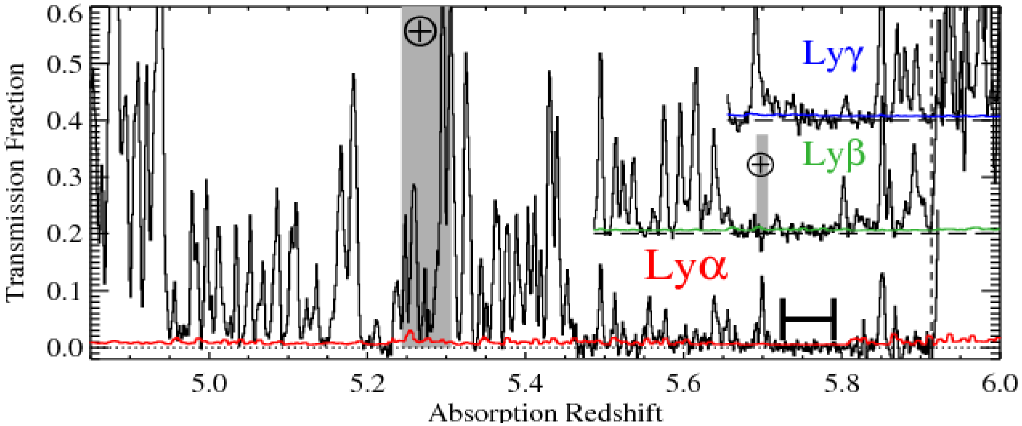
Outline

1. Introduction
2. Strong Langmuir turbulence and wave packet collapse
3. Line shape model
4. Results
5. Conclusion

Study of radiative properties of plasmas

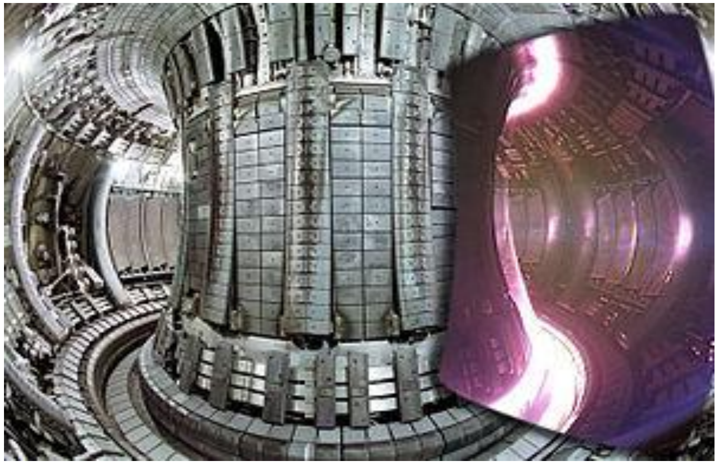
Line shapes for a plasma diagnostic

-Broadening : Stark effect



Applied to
-Laboratory plasmas
-Fusion
-Astrophysics

Astrophysics



tokamak JET, ITER

Modeling of plasma radiative properties

Numerical simulation

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

Stochastic process

Statistical properties of the plasma and waves

Plasma turbulence

Many different phenomena

Interstellar turbulence : gas velocities are not of pure thermal origin

Laboratory, fusion plasmas : Tokamak strongly affected by turbulent transport. Modeling uses fluid and kinetic theory

We examine here only the conditions of **strong Langmuir turbulence (wave collapse)** which appear if the plasma is coupled to an energy source (beam of particles)

Strong Langmuir turbulence: when and where?

-We use the ratio *W* of the wave energy density to the plasma energy density

$$W = \frac{\varepsilon_0 \left|\vec{E}\right|^2}{4 N_e k_B T_e}$$

There is a threshold in *W* depending on the plasma conditions

-Wave collapse/strong Langmuir turbulence are thought to exist in a huge range of conditions:

over 23 orders of magnitude of N_e, 4 orders in *T*, 15 orders in *E* !

Planetary foreshocks, Auroral regions, ionosphere,

electron beams, laser plasma, fusion plasmas

Many experimental signatures, what about spectral line shapes?

Birth of Strong Langmuir turbulence

Three linear waves in a plasma:

1-Electronic wave at the plasma frequency $\omega_p = \sqrt{\frac{N_e e^2}{m\varepsilon_0}}$

2-Ion acoustic wave involve density fluctuations, they have a constant velocity c_S (plasma sound speed)

3-Electromagnetic waves

The amplitude of waves grows in presence of a beam of particles

Nonlinear coupling of waves 1-2-3 is described by the Zhakarov equations or by numerical simulations

The physical properties of the plasma are changed :

We enter in the **strong Langmuir turbulence** regime

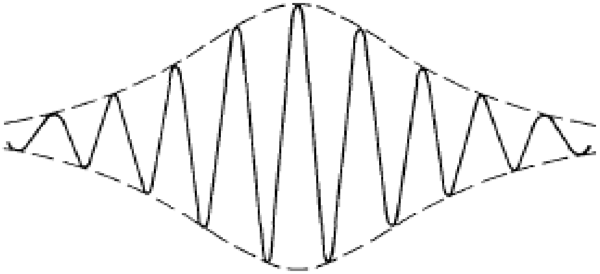
The creation of wave packets

-Density fluctuations create low density regions

-Wave packets localize and grow in such low density regions with a high refractive index

-Modeling: Zhakarov equations reduce to the nonlinear Schrödinger equation in the adiabatic approximation
One dimensional solution : **stable soliton**

$$i\frac{\partial E}{\partial t}+\frac{\partial^2 E}{\partial x^2}+c_S^{-2}|E|^2 E=0$$



Wave packet cycle, spatial structure

2 and 3 D simulations reveal

-The existence of a wave packet cycle:

wave packets form, collapse, dissipate, then reform

For plasmas with T≈10^4 K, $10^{14} < N_e < 10^{19}$ m^{-3},

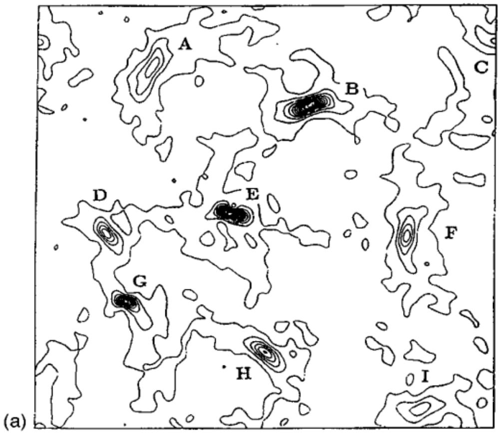
the time for a cycle in the range 30-70 ω_p^{-1}

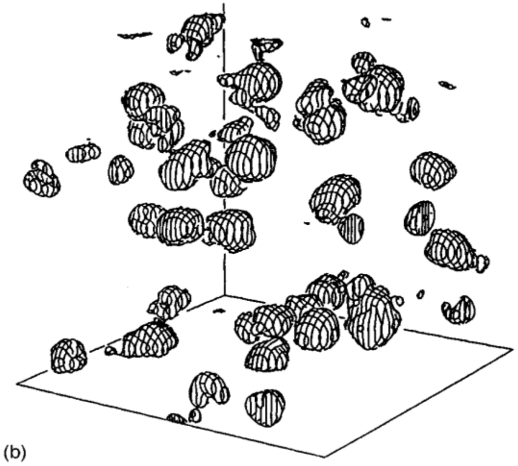
-The spatial structure of localized wave packets:

Dense packing, mean interpacket separation about 2 to 3 times of the packet length scale

Many wave packets on a line of sight

2 D





3 D Contours of high wave energy

Line shape with strong Langmuir turbulence

Model for the electric field felt by an atom near to a wave packet

$$\vec{E}(t) = \left\{ \begin{array}{ll} \vec{E}_1 \cos(\omega_p t + \varphi_1) S_1(t), & 0 \le t \le t_1 \\ \vec{E}_2 \cos(\omega_p t + \varphi_2) S_2(t), & t_1 \le t \le t_2 \\ \vdots & \\ \vec{E}_n \cos(\omega_p t + \varphi_n) S_n(t), & t_{n-1} \le t \le t_n \\ \vdots & \end{array} \right\}$$

Renewal stochastic process, with for each jump a new electric field magnitude, direction and phase.

We can choose:

-the envelope functions $S_j(t)$ and their shape

-the probability density function (PDF) for the modulus E

-the waiting time distribution (WTD) between two sucessive jumps

Renewal process for the electric field

-Gaussian PDF for the electric field

-An exponential WTD for the jumping times $J(t)=\nu \exp(-\nu t)$

The jumping frequency ν is taken equal to the inverse of the average duration of a wave packet cycle (Robinson 1997)

-A Lorentzian envelope functions $S_j(t)$ with a time width ΔT_L having a constant ratio with the step duration τ

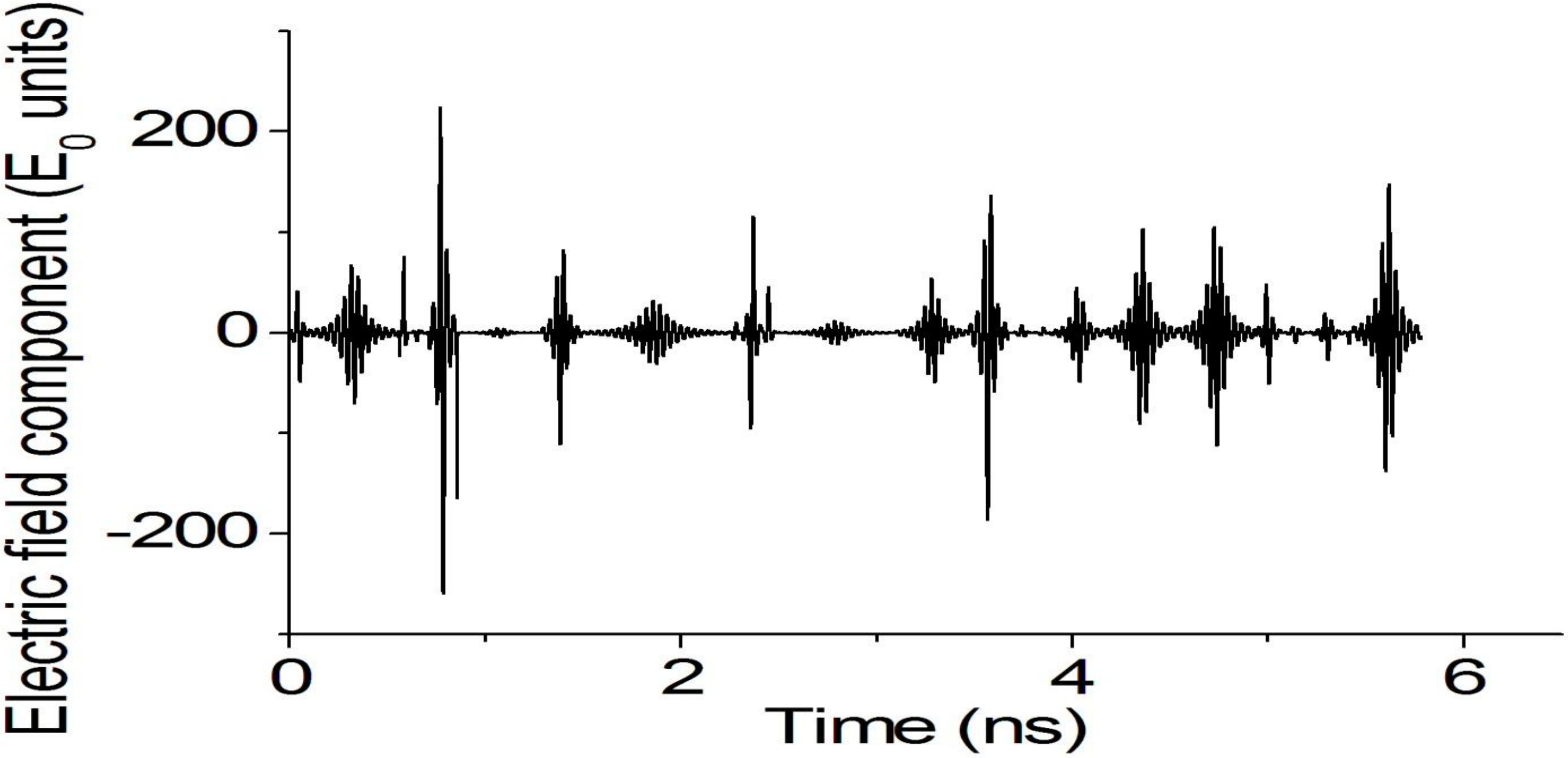
We use a **simulation** of the stochastic renewal process

Electric field history

Average peak field 150 E_0 (E_0 :average plasma microfield), jumping frequency $\nu=\omega_p/37$

plasma T= 10^5 K, $N_e=10^{19}$ m^{-3}

Lorentzian envelope functions $S_i(t)$ with a time width ΔT_L 20% of τ



Dipole autocorrelation function and the line shape

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

D is the emitter dipole, C(t) obtained by solving the Schrödinger equation

The dipole autocorrelation function (DAF) is obtained after an average over all configurations of the turbulent Langmuir field

In the following we average over 10^4 field histories

The profiles are computable by Fourier transformation of the DAF

Calculations for the hydrogen lines

L_α, L_β and H_α lines without fine structure

Different calculations are possible

-The single effect of strong Langmuir turbulence (soliton)

-The effect of equilibrium Stark broadening (pure Stark)

-The result of a convolution of the two previous (full profile)

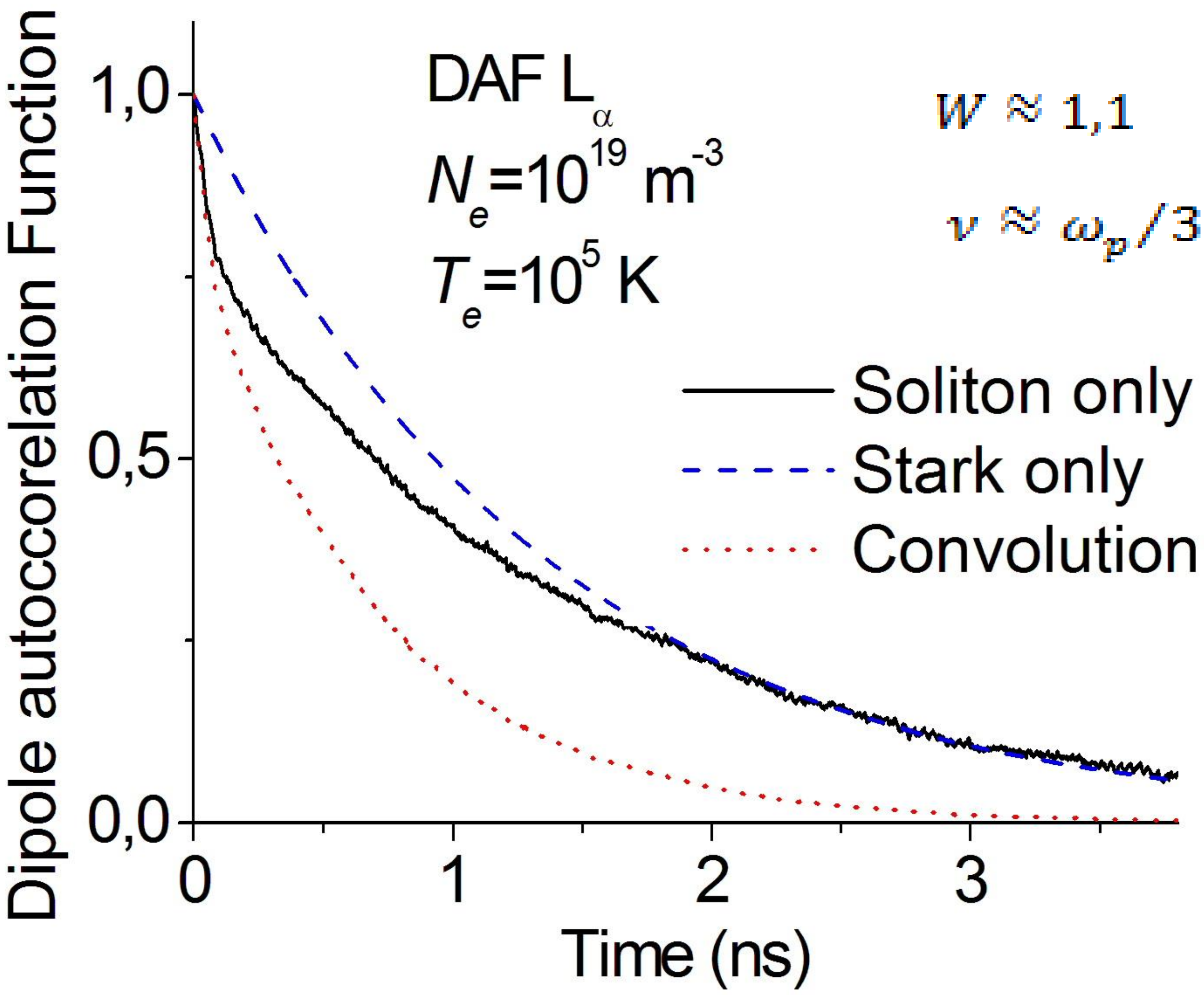
line shapes calculated in the center of mass for radiative transfer studies in fusion (Rosato et al. 2010)

First results:

I. Hannachi et al., EPL 114, 23002 (2016)

R. Stamm et al, EPJD 71, 68 (2017)

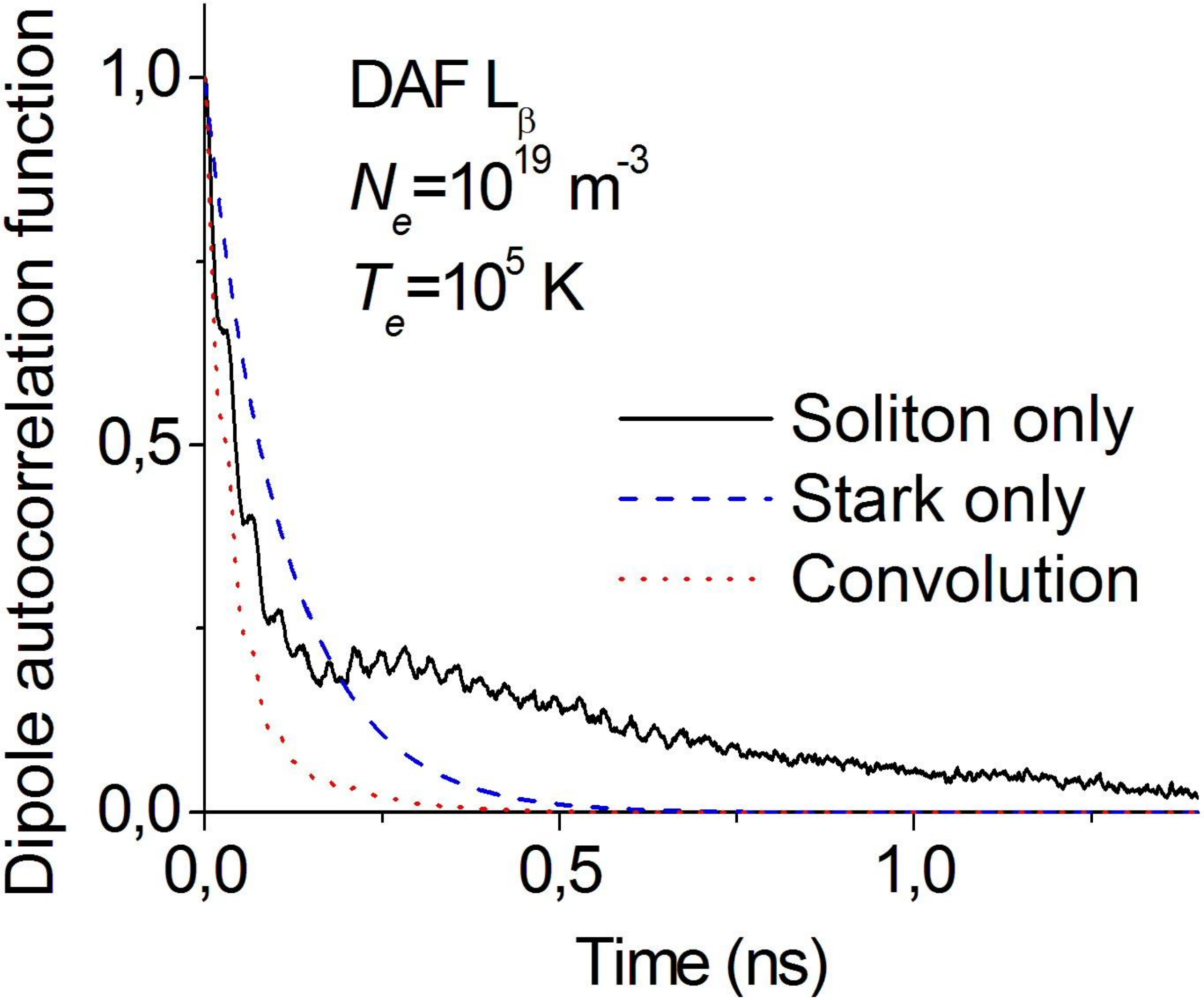
Dipole autocorrelation function of L_α



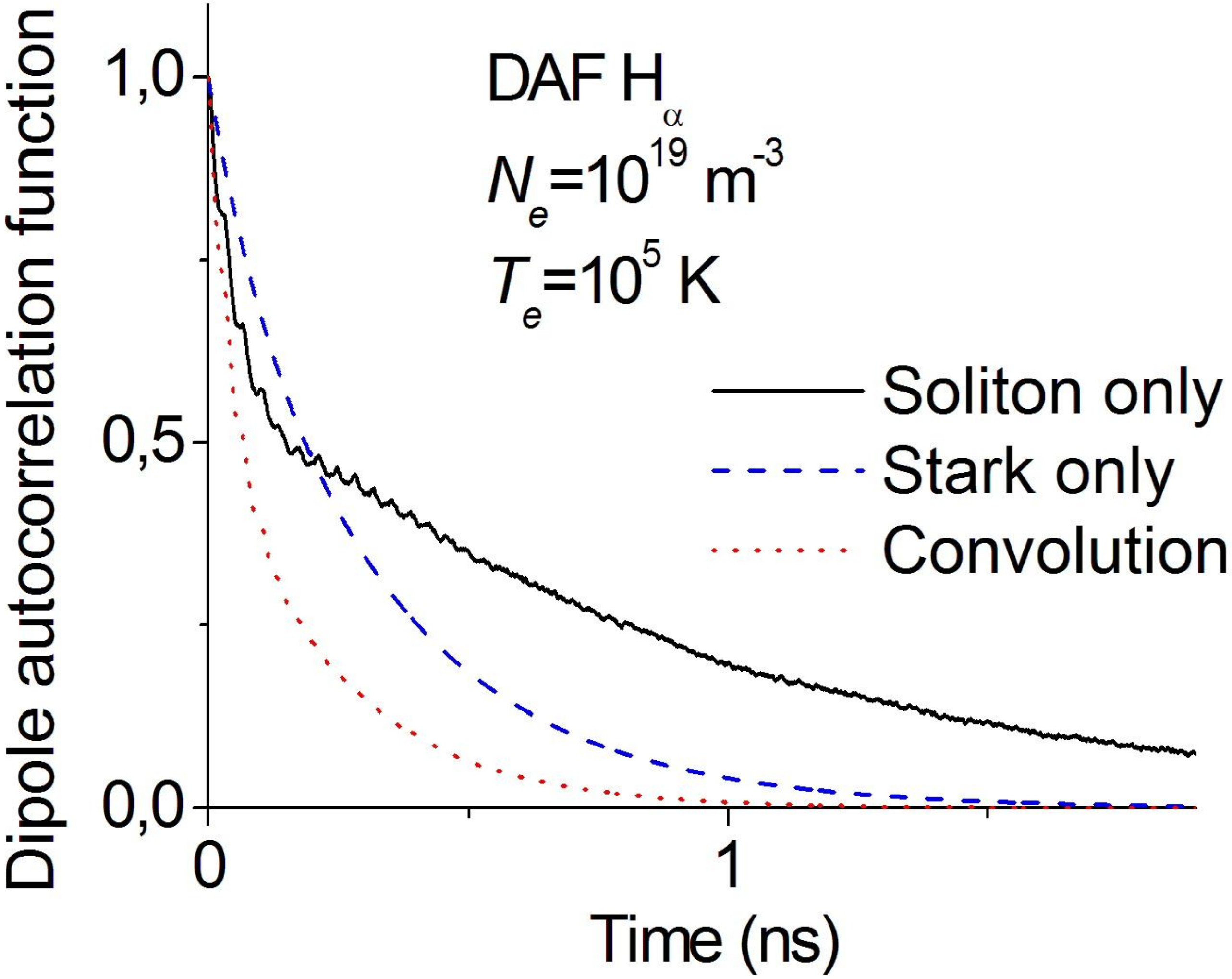
$$W \approx 1{,}1$$

$$\nu \approx \omega_p/37$$

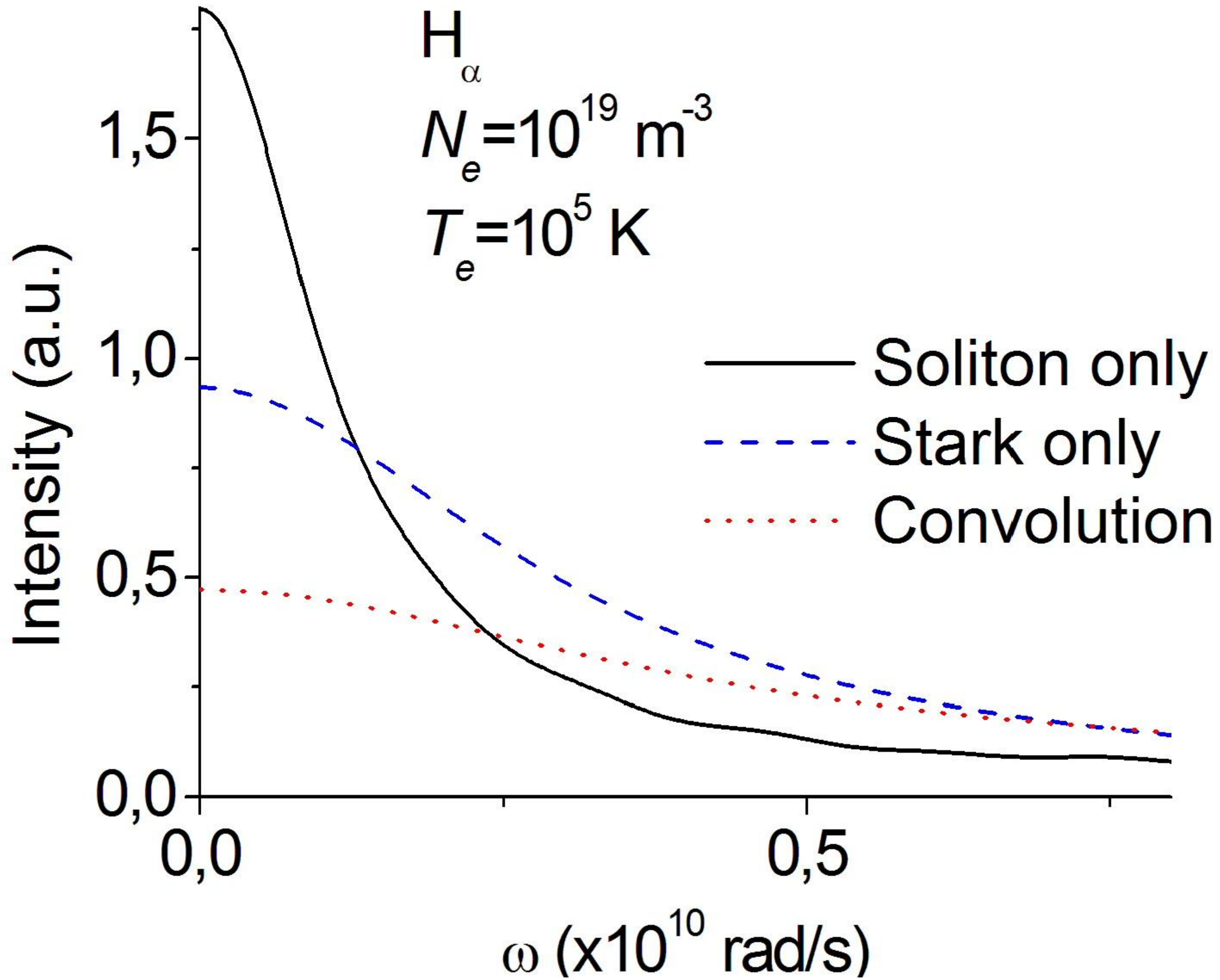
Dipole autocorrelation function of L$_\beta$



Dipole autocorrelation function of H_α



Line shape broadening of H_α



Summary

In presence of an intense energy source, coupling nonlinearly the plasma waves, strong Langmuir turbulence can develop in a plasma

Numerous wave packets appear and evolve in the plasma

The electric field peak values may be locally 2 to 3 orders of magnitude larger than the average plasma microfield

A stochastic model has been proposed for calculating the effect of strong turbulence on a line shape

Our model predicts a strong additionnal broadening in the case of the hydrogen L_α , L_β and H_α lines