Progress on radiative transfer modeling in edge plasmas

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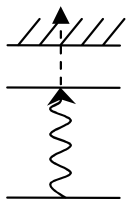
Introduction

Tokamak edge and divertor plasmas can be optically thick to the neutral hydrogen radiation

The photon absorption provides
a source of excited atoms
They can ionize more easily



“Photo-induced”
ionization

Consequences for ITER?
Efforts in theory and modeling are currently ongoing

1) Opacity effects in magnetic fusion

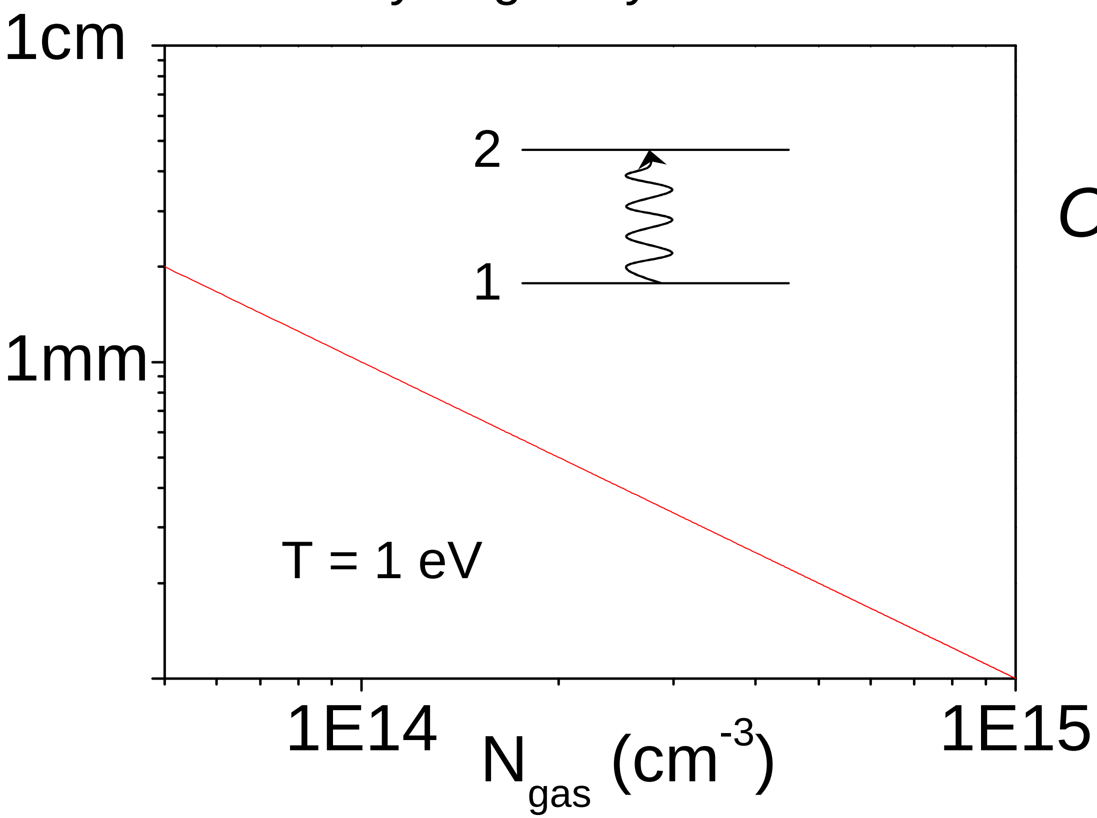
2) A transport model for radiation in fluctuating medium

Photon mean free path estimates

$$\text{monochromatic mean free path} \propto \frac{1}{N_{gas}}$$

Mihalas, Stellar Atmospheres

Hydrogen Lyman α



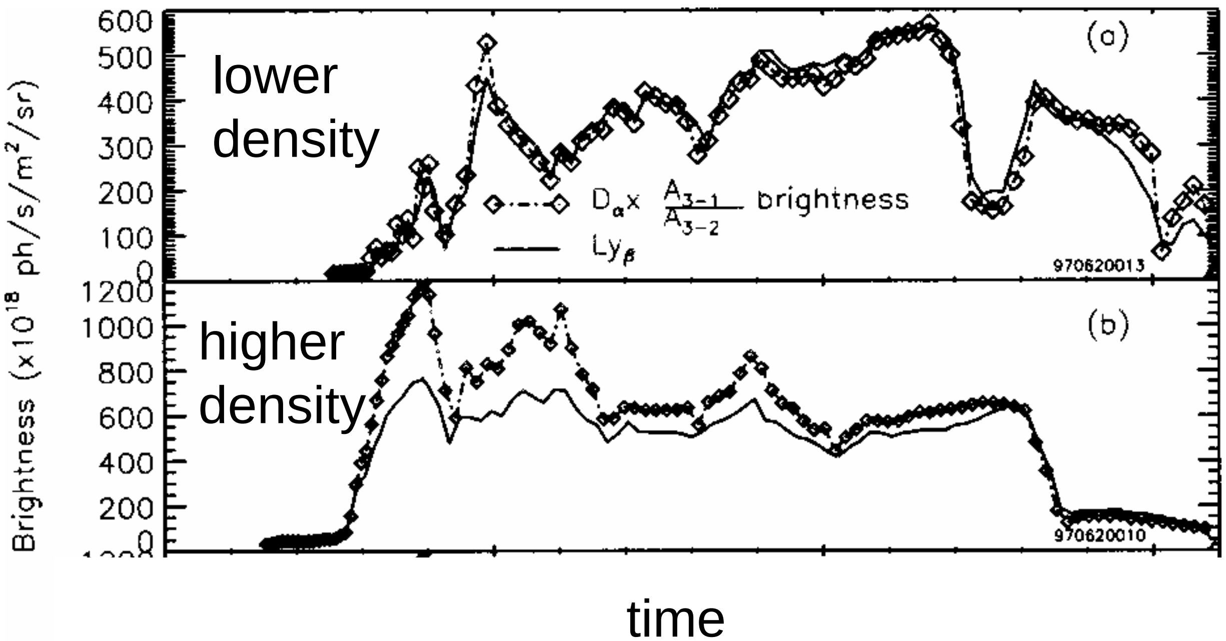
Opacity: large N x L machines

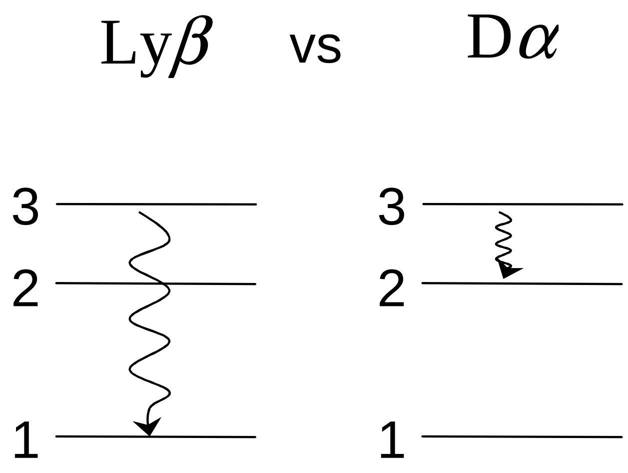
ITER & DEMO

Experimental observations: Lyβ/Dα

Ratio Lyβ / Dα in Alcator C-Mod: proof of opacity
in high-density divertors

J. L. Terry et al., PoP (1998)

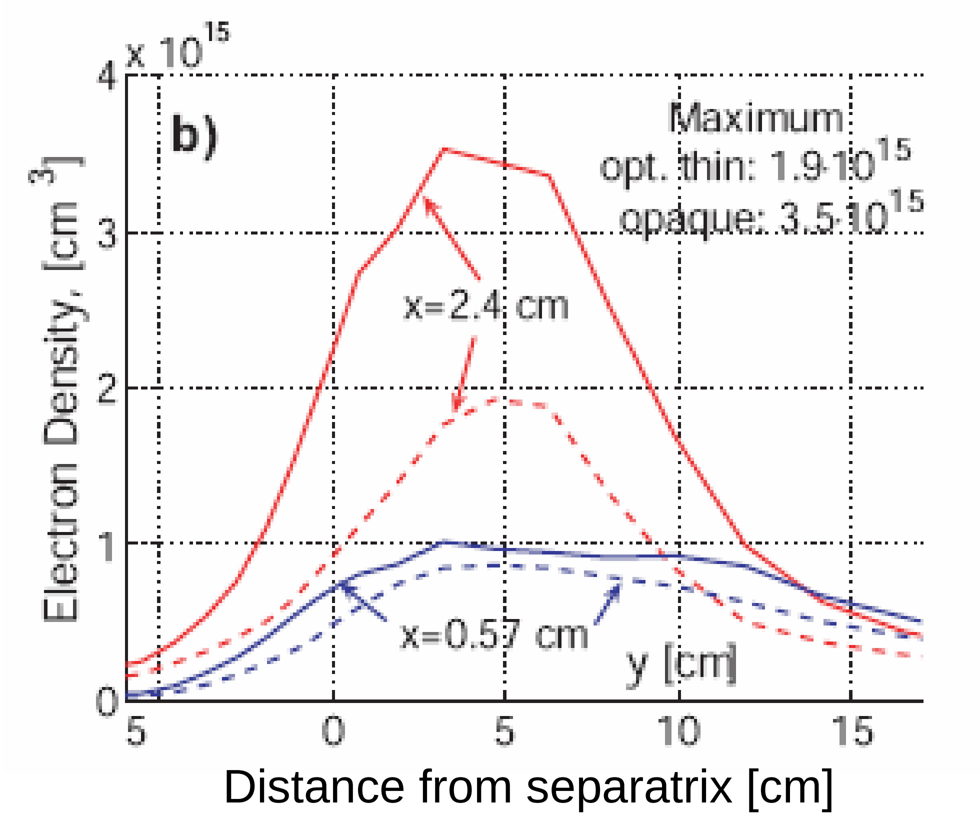


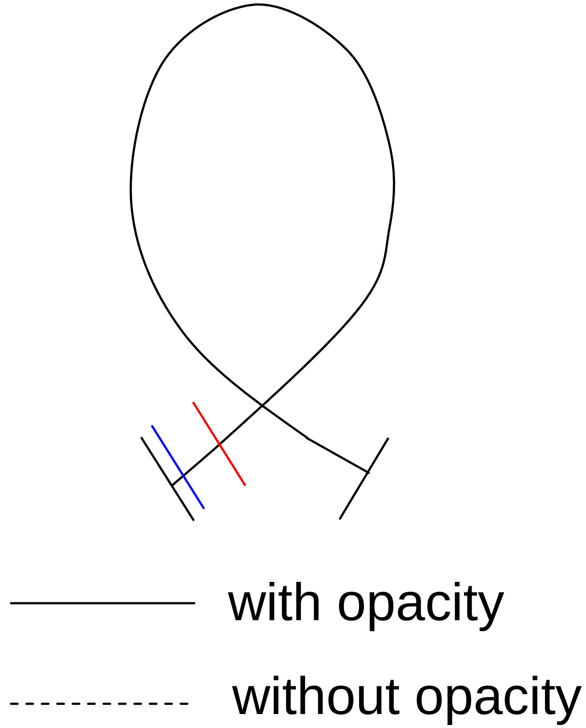


Similar observations at JET, but somewhat weaker

Numerical simulations: ITER

B2-EIRENE code (www.eirene.de)
Kotov, Reiter, Kukushkin et al., CPP (2006)





The electron density profile in the divertor is affected by line-radiation opacity

The transport model

i) D-atoms in their fundamental state (n = 1):
Boltzmann equation by Monte-carlo method

ii) Excited D-atoms (n > 1): stationary collisional-radiative model

iii) The charged particles: fluid model (B2 code)

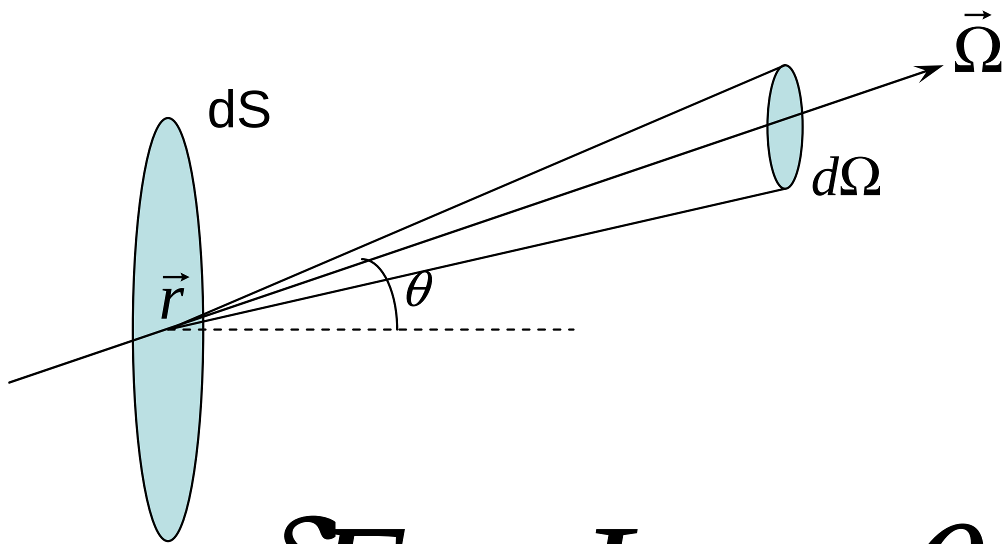
iv) Photons: kinetic approach, Monte-Carlo method

Radiative transfer formalism

Topic associated with astrophysics, ICF

Fundamental quantity of interest = "radiation specific intensity"

$$I(\omega, \vec{\Omega}, \vec{r}, t)$$



$$\delta E = I \cos\theta \, d\omega d\Omega dS dt$$

The equation of transfer

A linear, Boltzmann-like transport equation

$$\frac{1}{c}\frac{\partial I}{\partial t} + \vec{\Omega}\cdot\frac{\partial I}{\partial \vec{r}} + \chi I = \eta$$

χ absorption

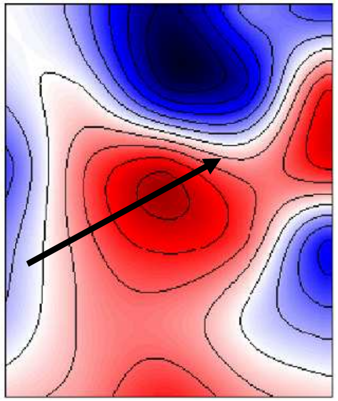
η spontaneous emission

Not retained here:
- Stimulated emission (low radiation intensity, no pop. inversion)
- Scattering (complete redistribution)

Plasma fluctuations

All of the numerical investigations done so far were made assuming a plasma background whose typical variation scales are much larger than the neutrals & radiation transport scales

This is questionable
for tokamaks: $l_{turb} < 1$ cm



Statistical approaches have been proposed recently for neutrals
Y. Marandet et al., PET 2009; PPCF (2011)
A. Mekkaoui et al., P1-6

Radiation transport?

Setting-up the formalism

i) Coarse-graining in time

$$I(\omega,\vec{\Omega},\vec{r},t) \rightarrow \langle I \rangle(\omega,\vec{\Omega},\vec{r},t) = \frac{1}{T}\int_t^{t+T} dt'\, I(\omega,\vec{\Omega},\vec{r},t')$$

ii) Decomposition

$$I = \langle I \rangle + \delta I \qquad \chi = \langle \chi \rangle + \delta\chi \qquad \eta = \langle \eta \rangle + \delta\eta$$

A quasilinear-type model

G. C. Pomraning,
Linear Kinetic Theory and Particle Transport in Stochastic Mixtures (1991)

The model is suitable for regimes where $l_{turb} << l_{mfp} \sim <\chi>^{-1}$

$$\left(\vec{\Omega}\cdot\vec{\nabla}+\langle\chi\rangle\right)\langle I\rangle=\langle\eta\rangle-\langle\delta\chi\delta I\rangle$$

$$\left(\vec{\Omega}\cdot\vec{\nabla}+\langle\chi\rangle\right)\delta I=\delta\eta-\delta\chi\langle I\rangle+\cancel{\langle\delta\chi\delta I\rangle}-\cancel{\delta\chi\delta I}$$

$$\delta I=\left(\vec{\Omega}\cdot\vec{\nabla}+\langle\chi\rangle\right)^{-1}\left(\delta\eta-\delta\chi\langle I\rangle\right)$$

Coarse-grained transport equation

$$\left(\vec{\Omega} \cdot \vec{\nabla} + \chi_{eff}\right)\left\langle I \right\rangle = \eta_{eff}$$

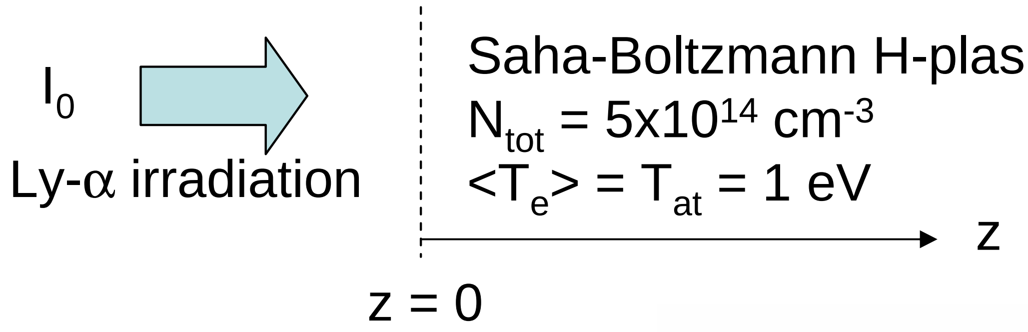
$$\chi_{eff} = \left\langle \chi \right\rangle - \int_0^\infty ds \left\langle \delta\chi(\vec{r})\,\delta\chi(\vec{r} - \vec{\Omega}s) \right\rangle e^{-\langle \chi \rangle s}$$

$$\eta_{eff} = \left\langle \eta \right\rangle - \int_0^\infty ds \left\langle \delta\chi(\vec{r})\,\delta\eta(\vec{r} - \vec{\Omega}s) \right\rangle e^{-\langle \chi \rangle s}$$

Homogeneous case: $<\chi>$, $<\eta>$ are space independent

In the absence of fluctuations,
the standard radiative transfer equation is recovered

Attenuation of a radiation pencil

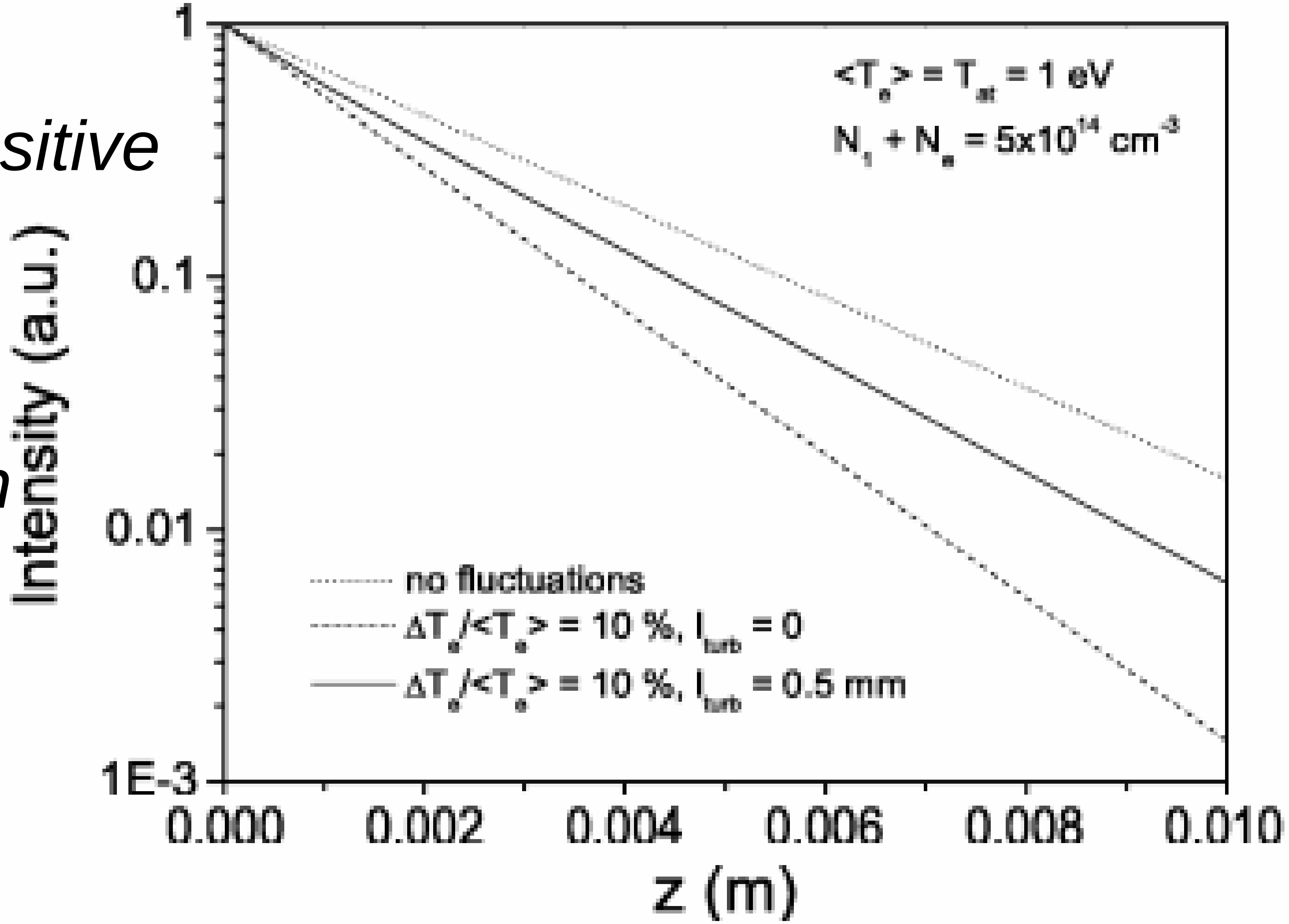


Saha-Boltzmann H-plasma
$N_{tot} = 5\times10^{14}$ cm^{-3}
$\langle T_e \rangle = T_{at} = 1$ eV

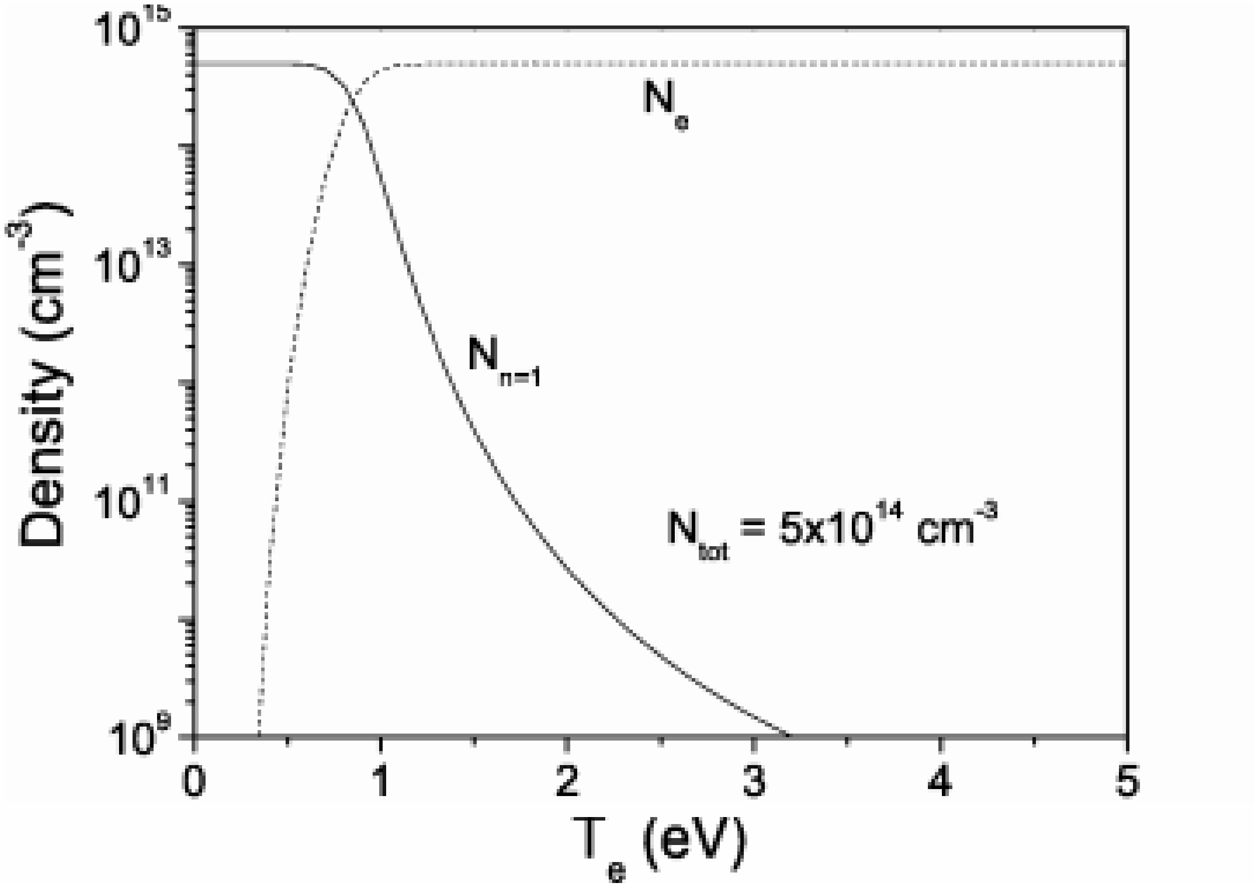
- Gamma PDF for T_e-fluctuations
- Exponential correlation
- Doppler line shape

i) The penetration is sensitive to the plasma fluctuations

ii) The spatial correlation reduces the global opacity



Why is the penetration sensitive to fluctuations?



$$\chi \propto N_{n=1}$$

The absorption coefficient χ is strongly dependent on T_e

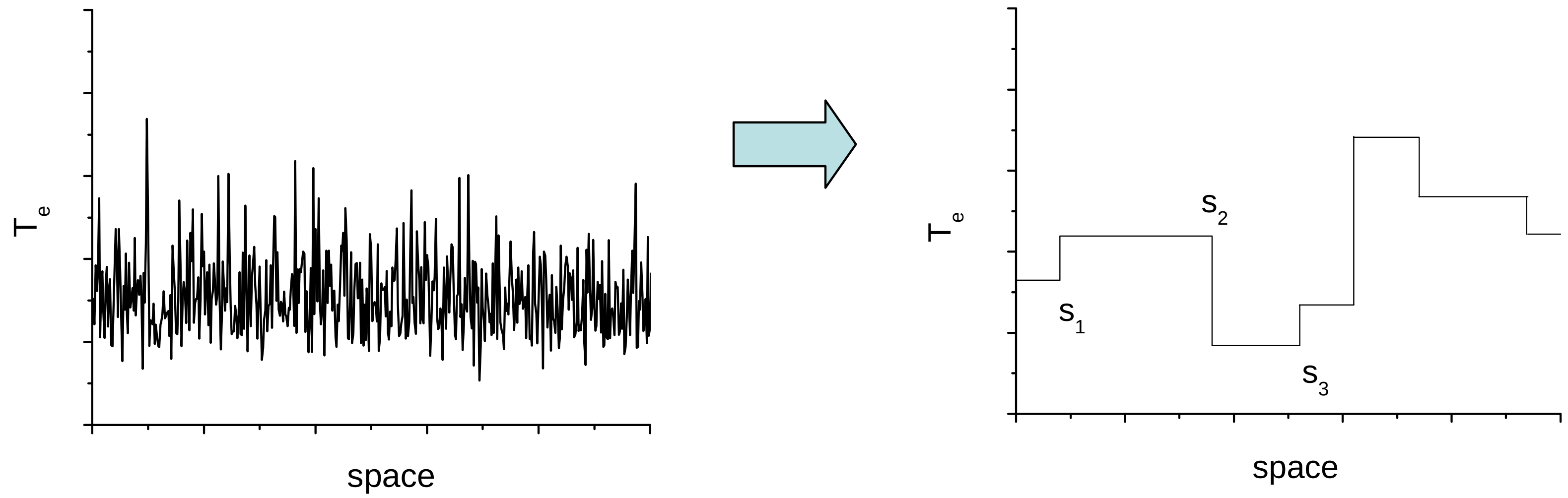
$$\langle\chi(T_e)\rangle \neq \chi(\langle T_e\rangle)$$

Similar result for the emission coefficient

Beyond the small l_{turb}/l_{mfp} limit?

"The method of model coefficients"

A. Brissaud and U. Frisch, J. Math. Phys. (1974)



- Same result as from the quasilinear theory (QLT) in the limit $l_{turb} \rightarrow 0$
- As in the QLT, use of the 1-point PDF and the spatial correlation function

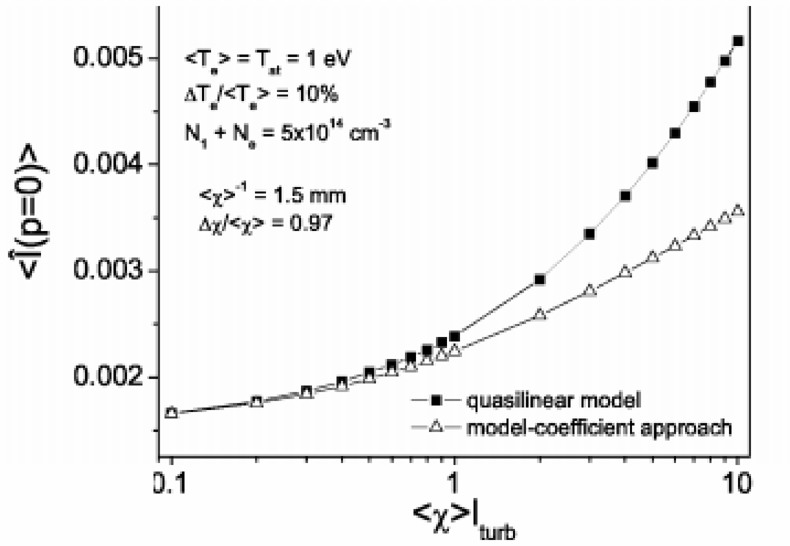
Laplace transform

$$\left\langle \tilde{I}(p) \right\rangle = \frac{\left\langle \left(p + 1/l_{turb} + \chi\right)^{-1} \right\rangle}{1 - \frac{1}{l_{turb}} \left\langle \left(p + 1/l_{turb} + \chi\right)^{-1} \right\rangle} I_0$$

Behavior at large z

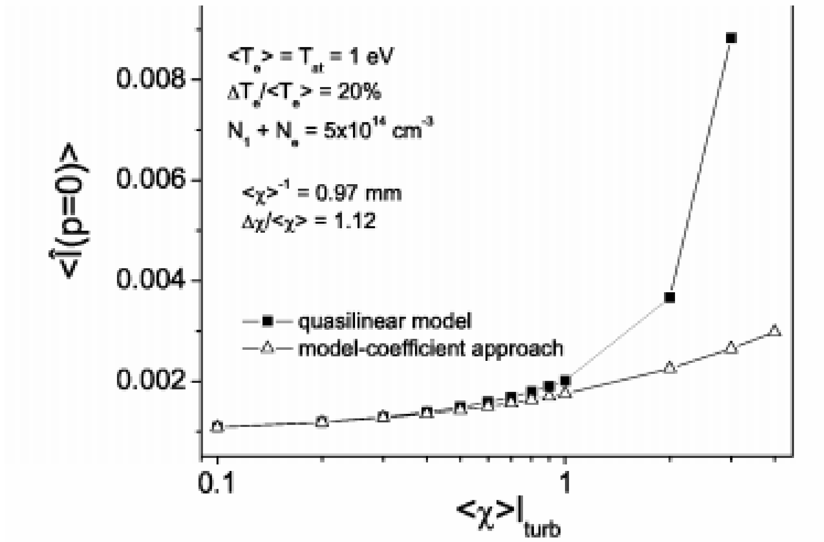
i) $\left\langle \tilde{I}(p=0) \right\rangle$ at $\Delta T_e/\langle T_e\rangle$ = 10 %

The QLT is in a rather good agreement with the model-coefficient approach (max. ~40 % deviation)



ii) $\left\langle \tilde{I}(p=0) \right\rangle$ at $\Delta T_e/\langle T_e\rangle$ = 20 %

Deviations are much stronger
This is a feature of large fluctuations:
here $\Delta\chi/\chi > 1$



Summary

Opacity in Lyman series is omnipresent in divertor plasmas with large NxL: Alcator C-Mod, ITER, commercial fusion reactor?

Line radiation trapping can be accounted for in edge simulations by a kinetic approach

The radiation field is affected by plasma fluctuations: here, illustration with a simple transport model

Self-consistent atom-photon simulations?