ON THE INFLUENCE OF TURBULENT FLUCTUATIONS ON AM/PMI DATA FOR EDGE PLASMA MODELING

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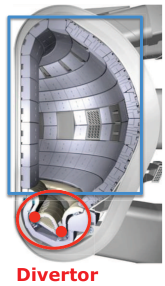
Introduction – Power exhaust in tokamaks

✓ In steady state, the fusion energy has to be extracted



ITER : P_{fus} = 500MW → 400 MW neutrons → > 500 m²

→ 100 MW α particles + 50 MW heating (Q=10) → ~ 1 m²

Spreading the energy is *mandatory*

✓ Transport codes used to address these issues

Turbulence averaged out :

Turbulent transport coefficients = free parameters

Effect of averaging on AM and PWI physics ?

Outline

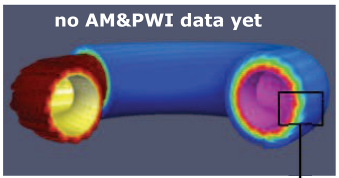
1) Derivation of transport equations
2) Transport of neutral particles in a turbulent plasma
3) Ionization balance in turbulent plasmas

Can we capture the effects discussed in 2) and 3) using "fluctuation dressed" AM/PWI data ?

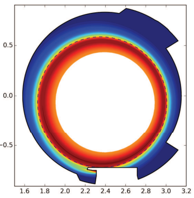
4) Conclusions and Perspectives

1- Derivation of transport equations

Coarse graining level →



averaging → D_a, χ_a, ...



TOKAM3X *P. Tamain et al.*

TOKAM2D

SolEdge2D *H. Bufferand et al.*

Y. Sarazin and Ph. Ghendrih, PoP 1998

Averaging issues in transport codes

✓ Mean turbulent fluxes and their origin

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = S \qquad n = \langle n \rangle + \delta n \qquad \mathbf{v} = \langle \mathbf{v} \rangle + \delta \mathbf{v}$$

Averaging issues in transport codes

✓ Mean turbulent fluxes and their origin

$$\frac{\partial \langle n \rangle}{\partial t} + \nabla \cdot [\langle n \rangle \langle \mathbf{v} \rangle + \langle \delta n \; \delta \mathbf{v} \rangle] = \langle S \rangle$$

✓ How to express $\Gamma_{turb} = \langle \delta n \delta \mathrm{v} \rangle$ in terms of <n> ?

$\Gamma_{\mathrm{turb}} = -D_a \nabla \langle n \rangle$ « ***Gradient diffusion hypothesis*** »

✓ Issues associated to averaging of source terms

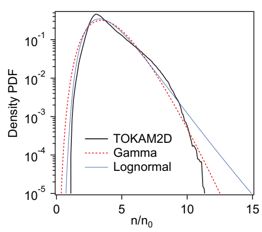
Parametric **nonlinearities** $\langle S(T_e) \rangle \neq S(\langle T_e \rangle)$

Statistical **nonlinearities** $\langle n_z n_e \overline{\sigma \mathrm{v}} \rangle \neq \langle n_z \rangle \langle n_e \rangle \langle \overline{\sigma \mathrm{v}} \rangle$

i) Size of the effects ? **ii) How to take this in account ?**

Main features of SOL fluctuations

✓ The density PDF can be fitted to a *gamma distribution*



$$W(n) = \frac{1}{\Gamma(\beta)\alpha^\beta} n^{\beta-1} \exp\left(-\frac{n}{\alpha}\right)$$

$$\langle n(\mathbf{r},t) \rangle = \alpha(\mathbf{r})\beta(\mathbf{r})$$

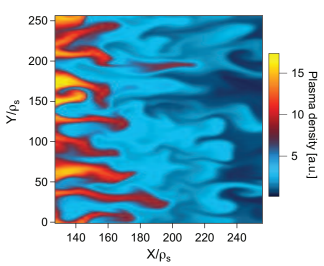
$$R = \frac{\sigma^{1/2}}{\langle n \rangle} = \frac{1}{\sqrt{\beta}} \sim 1$$

✓ Similar distribution for T_e

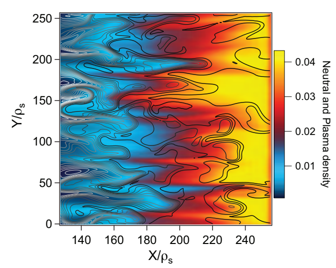
✓ Correlation time $\tau_c \simeq 10 \mu s$ Correlation length $\lambda \simeq 1cm$

Use this information to build stochastic models for fluctuations

2) Transport of neutral particles in turbulent plasmas

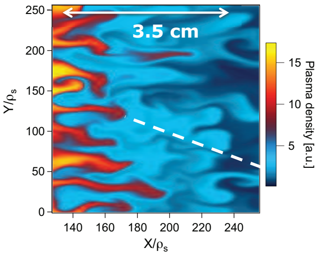


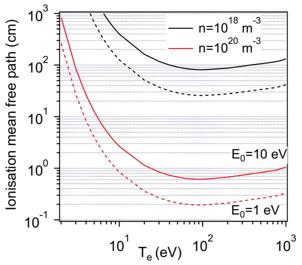
Plasma density [a.u.]



Atom density [a.u.]

Considerations on time and spatial scales



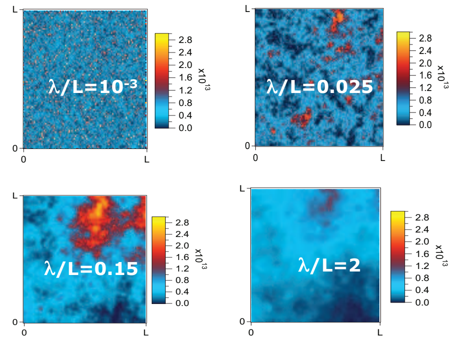


✓ **The fluctuations are often *frozen* during the neutral lifespan**

✓ **Atoms' mean free paths can be *large* compared to λ**

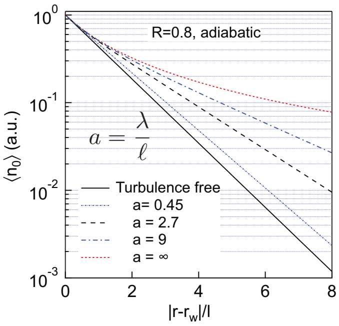
Exemples of sampled density fields

Multivariate generalization of the gamma distribution



Y. Marandet et al. PPCF 2011

Density fluctuations reduce the stopping power



Why is it so ?

Jensen's inequality on convex functions:

$$\langle e^{-x}\rangle \geq e^{-\langle x\rangle}$$

✓ **The effect of density fluctuations strongly increases with** a

✓ **Substantial for high relative fluctuations levels only (>30%)**

"Fluctuations dressed" ionization rate coefficient

✓ **How to implement these effects in transport codes ?**

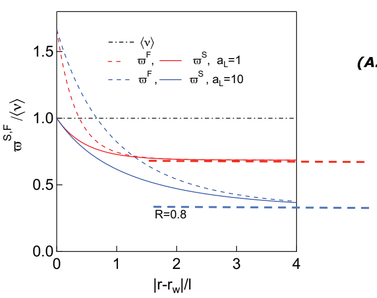
A possibility: fluctuations dressed rate coefficients

$$\langle S_n\rangle = -\varpi(s)\langle n_0\rangle = -\langle n_0\rangle\langle n\rangle[\overline{\sigma \mathrm{v}}]_{eff}(s)$$

"Fluctuations dressed" ionization rate coefficient

✓ **How to implement these effects in transport codes ?**

A possibility: fluctuations dressed rate coefficients



(A. Mekkaoui et al., PoP 2012)

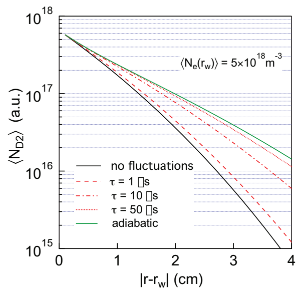
Szegö Limits

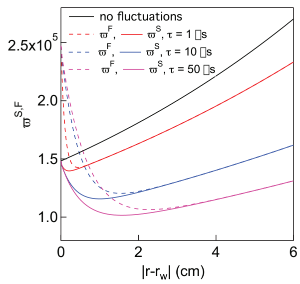
(Y. Marandet et al., PPCF 2011)

Examples in realistic conditions

✓ **D_2 more affected than D because mean free path shorter**

✓ **Time dependent effects taken into account**

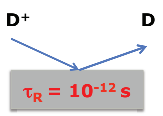




(Y. Marandet et al., IAEA FEC Conference 2012)

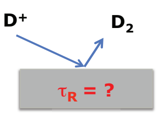
Role of the boundary conditions

✓ **So far: Γ_0 constant; what happens for recycling ?**



Backscattering

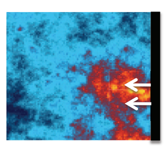
$$\Gamma_0(t) = \Gamma_{D^+}(t)$$

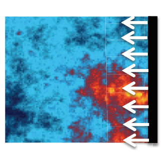


Molecule desorption

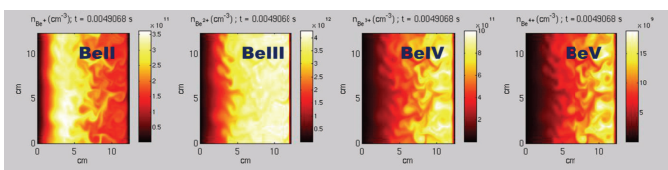
$$\Gamma_0 = \langle\Gamma_{D^+}(t)\rangle \text{ if } \tau_R \gg \tau_c$$

✓ **Effect on mean neutral particle penetration**



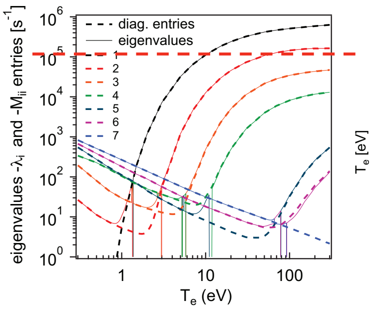


3- Effects of fluctuations on ionization equilibrium

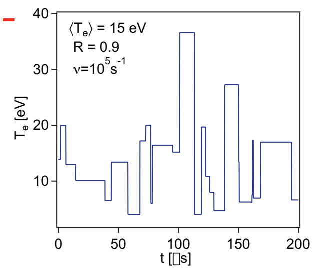


Time scales in the system

$$\frac{d\mathbf{N}}{dt} = \mathbf{MN} \qquad N = \{n_{C^0}, \dots n_{C^{6+}}\} \qquad \langle N \rangle \text{ ?}$$

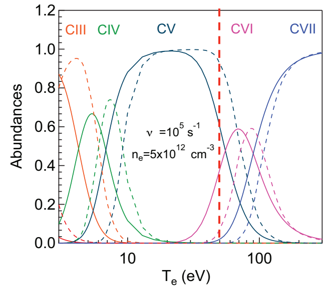


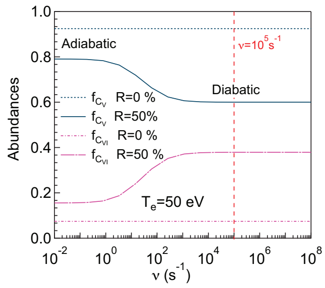
Kubo Andersen process



No separation of scales **valid over the whole temperature range**

Discussion of the results



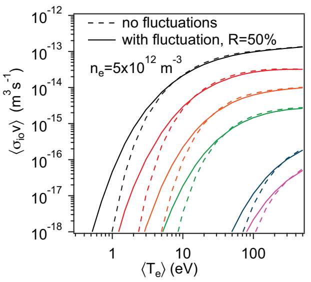


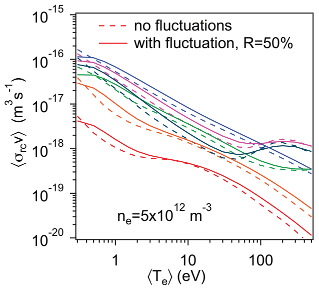
- ✓ **Ionization stages shift towards *lower temperatures***
- ✓ **The system is in the *diabatic regime*** $\langle \mathbf{M} \rangle \langle \mathbf{N} \rangle = 0$

F. Catoire et al., Phys. Rev. A (2010)

Effective ionization/recombination coefficients

$$\langle \overline{\sigma v} \rangle = \int_0^{+\infty} dT_e W(T_e) \overline{\sigma v}(T_e)$$ ***[as an non-maxw. rate coeff.]***

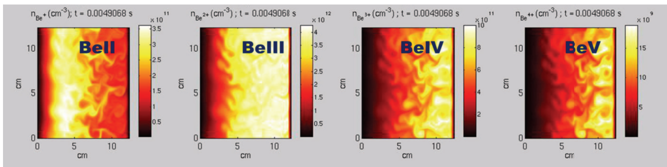




- ✓ **Increased ionization at low temperature**

Going beyond simple analytical models

- ✓ **Impurities introduced as passive scalars in TOKAM2D**

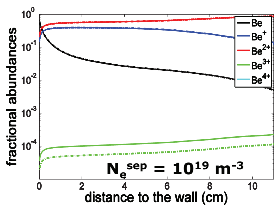


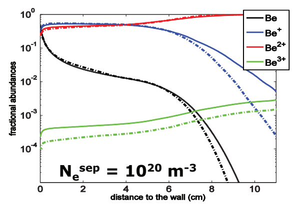
F. Guzman et al., J. Nucl. Mater. in press

- ✓ **Take transport into account:** $\Gamma_{\rm turb} = -D_a \nabla \langle n \rangle$
- ✓ **Address statistical correlations between n_e, T_e, n_z**
- ✓ **Compare sputtering yields to those obtained in mean fields calculations (first wall erosion) [on-going]**

Discussion of first results

- ✓ **Transport plays an essential role and *weakens* source averaging effects: transport to regions where rate coeff. are flat …**





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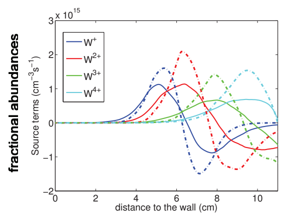

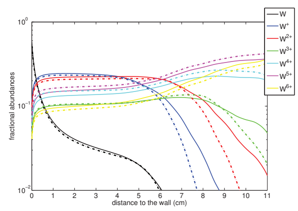

Good news, but W in divertor conditions might be more problematic

- ✓ **Calculation of effective data may be more difficult**

$$\overline{\sigma v}_{\rm eff} = \langle \overline{\sigma v} \rangle + \frac{\langle \delta n_e \overline{\sigma v} \rangle}{\langle n_e \rangle} + \frac{\langle \delta n_z \overline{\sigma v} \rangle}{\langle n_z \rangle} + \frac{\langle \delta n_e \delta n_z \overline{\sigma v} \rangle}{\langle n_e \rangle \langle n_z \rangle}$$

Conclusions

- ✓ **Evaluation of the strength of averaging effects on AM (and PMI) data *needed to assess related modelling uncertainties***
- ✓ **To do so, we used stochastic models for fluctuations**
- ✓ **In all cases, substantial effects only if fluctuation level > 30%**
- ✓ **Density fluctuations tend to reduce the screening efficiency of the plasma in particular for *molecules and impurities atoms***
- ✓ **Temperature fluctuations shift the local ionization balance towards lower temperatures**
- ✓ **In both these simplified cases, the effects can be accounted for by dressing AM data with fluctuations (when necessary !)**
- ✓ **More complex cases are likely to require either more information on fluctuations and/or further approximations**